REMOVAL OF LOW-LEVEL RADIOISOTOPES FROM WASTE WATER BY AEROBIC METHODS OF TREATMENT

By

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This investigation evaluated the removal of low-level radionuclides from waste water by a complete sewage treatment plant operating under field conditions. A pilot size treatment plant employing primary sedimentation, trickling filtration, and lagooning was utilized. These processes were subjected to a series of eight experiments involving phosphorus-32, iodine-131, potassium-42, cerium-141, 144, iron-59, cobalt-58, strontium-89, and mixed fission products.

The results indicated that primary sedimentation was relatively ineffective in removing colloidal and dissolved radionuclides from sewage. After two hours of continuous isotopic dosing, the effluent activity approached equilibrium conditions and the average rate of removal for all materials investigated stabilized at approximately 9 per cent.

The effectiveness of the trickling filtration process in the treatment of low-level wastes was limited to the ability of the filter to remove the radioactive components from the main waste stream and to

concentrate them in the solids leaving the filter in a settleable form. All radionuclides experienced significant uptake in the filter but, in some cases, extensive re-entrainment occurred before final removal could be effected. Consequently, the treatment efficiency of the over-all process was controlled by the removal accomplished by secondary sedimentation. The following treatment efficiencies were observed under equilibrium conditions: 60 to 70 per cent for iron-59 and cobalt-58; 40 to 50 per cent for cerium-141, 144 and mixed fission products; approximately 25 per cent for potassium-42 and strontium-89; and less than 5 per cent for iodine-131 and phosphorus-32.

Uptake studies indicated that the removal of low-level radionuclides within the filter resulted from the concentration of these materials by the zoogleal slimes present throughout the unit. The various rates of removal with respect to time were comparatively high during the initial doses but gradually decreased to equilibrium conditions which, for all materials investigated, were attained after approximately 96 doses. All rates of removal with respect to depth decreased somewhat exponentially with increasing depth of medium. Optimum filter depth was six feet.

The concentration of radioactive materials by the zoogleal slimes resulted from the action of three mechanisms, (a) absorption of the radionuclides by the microbiota in the slime layer, (b) ion exchange reactions involving the radioisotopes in the waste stream and the stable elements associated with the filter solids, (c) adsorption and physical trapping of the radioactive materials in and on the slime layer. Absorption and ion exchange appeared to be comparatively ineffective and highly reversible, especially for radioactive materials present in their

soluble form. Adsorption and physical trapping were indicated to be efficient and relatively irreversible for colloidal radionuclides.

Lagoon studies indicated that the long detention time and intimate algal-bacterial contact provided by this process were effective in diluting, delaying and, in most cases, substantially removing "slugs" of low-level radioactive materials. The basin had an effective detention time of two days and achieved the following removals: approximately 90 per cent for cerium-141, 144 and iron-59; 69 per cent for strontium-89; 50 to 60 per cent for phosphorus-32, cobalt-58, and mixed fission products; and less than 1 per cent for iodine-131.

The mechanisms indicated to be effective in the removal of radioactive materials by lagooning were precipitation by chemical, physical, and biological means and ion exchange reactions involving the suspended radionuclides and the stable materials retained in the basin. Trivalent materials in their colloidal form and divalent elements biologically significant in trace amounts were removed most effectively.

CHAPTER I

INTRODUCTION

With the discovery of X-rays by Roentgen in 1895 and of naturally occurring radioactive materials by Becquerel in 1896, the Nuclear Age was born. These events caused a sensation among physicists but aroused little interest in any other area. Twenty-four years later, it was announced that radioisotopes could be produced artificially. This gave renewed interest to the physicists and chemists but elsewhere radioactivity still seemed to be a scientist's toy with little, if any, practical application. Widespread interest in this new science was not initiated until 1942, when the first reactor was built and put into operation by Fermi and co-workers under the West Stands of Stagg Field at the University of Chicago. The success of this operation gave the young field of nuclear science an impetus that shows no signs of diminishing. These events gave rise to a new source of power -- both stationary and mobile -- and to a source of radioisotopes both of which have had a profound effect on industry, medicine and research.

The impact of this new technology upon the activities of man can best be illustrated by the use of a few statistics. In late 1955, there were 42 nuclear reactors known to be operating in the world with 29 of these in the United States (1). Twenty more were under construction, with nine of these in this nation (1). In 1960 there were almost 100 reactors in various stages of design and construction in the United

States alone (2). At that time, the U. S. Navy had approximately 61 seagoing reactors either existing or authorized as power plants for an aircraft carrier, a cruiser, a destroyer, and numerous submarines (2). In addition to these reactors, it is expected that in the near future almost every major college and university in the United States will have reactors for research and instructional purposes and with the exhaustion of fossil fuels, nuclear reactors will assume an increasing importance as a source of power. It has been estimated that by 1980, 65 per cent of all power plants will be operating on nuclear power (1).

As impressive as these figures may seem, they are not as phenomenal as those illustrating the growth in radioisotope usage in the past 17 years. In 1946, the first year the Atomic Energy Commission (AEC) made radioisotopes available to the civilian economy, there were only 86 users of these materials. The Oak Ridge National Laboratory, the principal supplier of radioisotopes in the United States, made 281 shipments totaling 8 curies (3). By 1959, a total of 78,598 shipments had been made to approximately 5,200 organizations and individuals licensed by the AEC (4). These shipments represented 537,781 curies of radioactivity (4). In 1962 about 1,100 shipments per month were sent to 2,700 users throughout the United States and 57 foreign countries (5).

There is reason to believe that even though the growth of the use of nuclear energy has been great, the surface of the application of this new tool has just been scratched. Myriad uses are in the research and developmental stage while others have yet to be realized or explored. However, we cannot accept the assets that nuclear technology offers to us unless we also assume the responsibility for the liabilities which we know to exist.

In practically all cases where radioisotopes are used, radioactive wastes are produced. As evidenced by the above figures, the treatment and safe disposal of these wastes could easily become the major problem which faces the Atomic Age. The extent to which we can safely dispose of our radioactive wastes could very well limit our exploration of this new science.

Aside from being a new problem for which we have no backlog of experience, radioactive waste disposal has certain features heretofore unencountered in the practice of waste treatment. For example, it is not possible, by normal physical or chemical means, to destroy or appreciably alter the property of radioactivity as we can the noxious properties of other pollutants. Furthermore, the maximum permissible levels for various radionuclides in waste effluents are several orders of magnitude lower than those for inactive contaminates. However, the most insidious property of this relatively new waste is that the biological effects of exposure to ionizing radiation, even at low levels, can be somatically and genetically cumulative and irreversible (6, 7, 8).

There are two alternatives in dealing with radioactive wastes, namely, (a) concentration and containment, and (b) dilution and dispersal. Concentrated or high-level wastes usually come in small volumes and the methods of disposal, even though expensive, are quite effective; consequently these wastes pose no serious public health problems. Dilute or low-level wastes come in large volumes and are usually discharged into the environment. It is the disposal of these wastes that is causing an increasing concern in the field of public health and placing an increasing burden on sanitary engineering.

The future release of low-level wastes by dilution into the environment must be carried out with caution and under strict controls. Even though the level of activity in the waste may be well within what is considered safe limits, it can be concentrated physically, chemically, and biologically in some phase of the environment, thus posing a health hazard to this or future generations. To prevent the possibility of such an occurrence, no effort should be termed excessive.

CHAPTER II

LITERATURE REVIEW

Throughout history man has been concerned with, and often plagued by, the wastes from his activities. In order to protect his health, comfort, and property he has been forced, often belatedly, to take remedial steps leading to the treatment and safe disposal of these detrimental products. The coming of the Atomic Age has once again presented this necessity; however, the incurable results will not allow us to wait until the situation becomes critical to take remedial steps.

The magnitude of the problem of radioactive waste disposal is not alarming until viewed in the light of present world activities and the predictions of future capabilities. It has been predicted that by 1965 the United Kingdom alone will be deriving 6,000 megawatts from nuclear power reactors (9). This annual capacity, which is scheduled to increase in subsequent years, will require the fission of 6 to 8 tons of uranium-235 and will produce an equivalent weight of fission products which will have an associated radioactivity of 10^9 curies (9). In the United States it has been estimated that the nuclear power industry will have produced about 3×10^9 curies of radioactivity in 27×10^6 liters of solution by 1970 and 6×10^{10} curies in 11×10^8 liters of solution by the year 2000 (10). Disturbing as these figures are, it must be remembered that they are estimates for merely the power reactors of only two countries. These figures must be augmented by the wastes from

all other reactors of all types in all countries as well as by the wastes from the rapidly expanding and diversified uses of radioisotopes in practically all disciplines of science. The escape of a small fraction of this activity as low-level wastes -- a highly probable occurrence -- could easily result in billions of gallons annually.

Since it is physically and economically impractical to concentrate low-level wastes, dilution into the environment is the only alternative. One of the most common and convenient methods of carrying this out is by discharge into the sewers (11, 12). Nevertheless, research concerning the ability of sewerage systems to receive and dispose of radioactive wastes has not been sufficient to permit formulation of comprehensive standards. Consequently, the legal limits of disposal of radioactive wastes in this manner are those outlined in Handbook 69 (13) for occupational exposure to various radionuclides in water. Admittedly, the values contained therein were not primarily intended for use in waste disposal, but they are well founded and offer a reasonable degree of safety until more applicable guide-lines can be developed.

Other than these limits, it is quite difficult to locate concrete information concerning the types and quantities of radioactive wastes that can be safely discharged into the sewers. Neal (14) states that the discharge of liquids to the sewers is safe if the average concentration of radioactivity in the sewer does not exceed 10^{-4} microcuries per milliliter and if the transient concentration does not exceed 10^{-1} microcuries per milliliter. He further states that these limits can be relaxed if the radioactivity is due solely to a nuclide of low toxicity. The Radio Corporation of America Service Company (15) gives some slightly

more specific information. Their recommended daily limits of discharged activity per million gallons of sewage are:

"1. One millicurie of strontium-90 or polonium-210.

2. One hundred millicuries of any radioactive material having a half-life of less than 30 days.

3. Ten millicuries of any other radioactive material."

These recommendations are rather brief and seem to be based more on rules-of-thumb than on the chemical, physical, or biological properties of the wastes or the ability of the sewage treatment plant to remove any fraction of the radioisotopes.

Once radioactive wastes are discharged to a sewerage system, the slimes in the plumbing and sewers provide the initial biological contact. Talboys (16), in a laboratory study of the retention of iodine-131 by bacterial slimes in drains, found that even though this isotope is not metabolized by the organisms in the slimes, small quantities are retained by physical adsorption and are subject to removal through successive flushing. He calculated that any hazard to sewer workers exposed to sewage bearing this isotope, would be quite low. Reid (17) made similar findings when studying the sorption and metabolic uptake of phosphorus-32 by bacterial slimes.

Considerable attention has been given to the effects of radioactivity on the organisms responsible for the biological treatment of sewage. Dobbins et al. (18), using oxygen utilization as a criterion for measuring oxidation rates in domestic sewage, found that these rates were not affected by phosphorus-32 in concentrations up to 1 millicurie per liter and only a small reduction in the rate of oxygen utilization was observed

at 10 millicuries per liter. Iodine-131 in concentrations up to 10 millicuries per liter produced a decrease in the rate of oxygen utilization which resulted in a reduction in the total oxygen demand of about 10 per cent by the seventh day.

The relative ease with which sludge digestion can be reduced to a small scale has induced considerable experimentation with this treatment process. Babbitt et al. (19), in laboratory studies with phosphorus-32, iodine-131, sulphur-35, and calcium-45 found that 100 millicuries per liter had no measurable effects but 200 millicuries per liter gave a 17 per cent reduction in gas. At the lower concentration, phosphorus was found primarily in the sludge phase, about 75 per cent of the iodine was in the liquid phase and about 90 per cent of the sulphur was found to be concentrated in the solids.

Phosphorus-32, iodine-131, and sulphur-35 were also used by Harmeson and Dietz (20) in their study of the effects of radioactive substances on sludge digestion. They found that 110 millicuries per liter had no apparent effects and 200 millicuries per liter were required to produce inhibitory effects. They also found that phosphorus and sulphur tended to concentrate in the sludge while iodine was more concentrated in the liquid.

Grune et al. (21, 22), using carrier-free iodine-131, could detect no significant difference in the gas production of their laboratory digestors when dosed with up to 300 millicuries per liter. At 600 millicuries per liter a significant reduction occurred in the reaction-velocity-constant but the ultimate gas production, volatile solids reduction, and concentration of volatile acids were not affected.

In further studies using carrier-free phosphorus-32, they found significant gas reductions at 200, 400, and 800 millicuries per liter. At the higher dose, a decrease in volatile matter and a tenfold increase in volatile acids were noted.

Primary treatment processes have received relatively little investigation with respect to their ability to treat radioactive wastes. Belcher (23), in a laboratory investigation concerned with some of the radioisotopes of interest in the medical profession, found that not more than 5 per cent of the influent activity was removed from domestic sewage when subjected to sedimentation.

Secondary treatment processes, on the other hand, have been involved in several investigations. Using laboratory scale trickling filters dosed with domestic sewage, Belcher (23) found that when bromine-82, iodine-131, sodium-24, phosphorus-32, and cobalt-60 were added to the sewage the concentration of radioisotopes in the effluent rose to an apparently steady value after 16 hours. The proportions of the radioisotopes removed were 6, 5, 13, 77, and 79 per cent, respectively.

Newall et al. (24) conducted laboratory investigations on the removal of plutonium from laundry wastes. They compared a trickling filter with chemical precipitation and concluded that the trickling filter, operating at a 15 to 1 recirculation ratio, gave effective removal and the resulting sludge volume was only about 4 per cent of that produced by chemical treatment of these wastes.

Gloyna and Geyer (25), using a synthetic laundry waste and rotary tubes, simulated an 8-foot trickling filter loaded at 8 million gallons per acre per day. They found that the slimes retained 40 per cent of

the applied cerium-144 and 20 per cent of the applied phosphorus-32. They concluded that the primary factors which control the removal of radioactivity by microorganisms are pH, viability of the organisms, type of isotope, toxicity of the waste to the microorganisms, and the ratio of stable to radioactive isotopes.

Carter (26), using 2-inch diameter laboratory filters dosed with sewage containing carrier-free iodine-131, found that a 6-foot filter had a removal efficiency of 85 per cent with most of the removal occurring in the first 3 feet. This removal efficiency was found to be fairly stable at dosing rates from 2 to 6 million gallons per acre per day.

In a laboratory study using a synthetic waste and a trickling filter 5 1/2 inches in diameter by 4 feet deep, Klein et al. (27) concluded that trickling filters could remove 70 to 85 per cent of the gross beta activity due to mixed fission products. They also found that the removal of phosphorus-32 was highly dependent upon the concentration of the stable phosphorus in the waste. In this respect, they reported that the removal of phosphorus-32 was as low as 20 per cent at a stable phosphorus content of 6 1/2 milligrams per liter and as high as 88 per cent when the stable phosphorus content dropped to 1 65/100 milligrams per liter.

Radioactive laundry wastes have also been studied by Wiederhold (28) who, using a trickling filter constructed from two 30-gallon drums, concluded that trickling filters not only gave satisfactory removal of the applied alpha and beta activities but also removal of organic materials that interfere with subsequent chemical coagulation and flocculation.

In treating radioactive laundry wastes of pH 3.0 to 5.0, BOD 200 to 800 milligrams per liter and beta activity of 180 disintegrations per minute per milliliter on single and two-stage laboratory trickling filters, Dobbins (29, 30) found the sludge to contain 200 times the activity of the raw waste. These studies indicated that 90 per cent of the gross activity of mixed fission products was removed at loadings of 250 pounds of BOD per acre-foot per day but that removal decreased with increasing loading rates. It was observed that the sludge activity was essentially independent of the organic loading rate but was dependent on the activity level of the waste. The percentage removal of the various elements were: cerium, 97 3/10; ruthenium, 79 1/10; strontium, 69 4/10; yttrium, 86 7/10; and zirconium-niobium, 79 1/2.

Fowler et al. (31) in studying the retention time of trickling filter slimes with rubidium, found that adsorption did take place but was inherently reversible. They observed a slow leaching of the activity from the filter for 37 hours after dosing occurred.

Activated sludge treatment as a means of radioisotope removal from liquid wastes was suggested by Ruchhoft (32) as early as 1949. Later, he and Setter (33) developed an activated sludge from synthetic sewage for the treatment of radioactive wastes. In subsequent laboratory work (34), they concluded that the activated sludge process is not efficient in removing isotopes that are not utilized by, or readily absorbed on biological floc (e.g. iodine-131), nor is it efficient for removing radioisotopes that are isotopically diluted with their stable counterparts (e.g. phosphorus-32). They did find, however, that the process gave good removal of plutonium even in the presence of organic sequestering agents.

Beicher (23), as a result of his laboratory research, concluded that the uptake of sodium-24 and bromine-82 by activated sludge from sewage is very slight. In both cases the proportion removed in a 6-hour aeration period was about 10 per cent.

Kaufman et al. (35, 36, 37), in their laboratory scale investigations of the removal of radioisotopes by the activated sludge process, arrived at the following conclusions.

1. Of the three isotopes studied, strontium-89 experienced the greatest removal with iodine-131 showing intermediate removal and phosphorus-32 undergoing the least removal.
2. The removal of radioisotopes, such as the three above, depends on carrier concentration and on the concentration of other isotopes that exhibit chemical similarity or interferences.
3. Batch studies show greater removal than those employing continuous flow and the removal increases with increasing solids.
4. With slugs of radioisotopes, greater removal is observed with high solids content but with continuous radioisotope flow, the converse is true.

Plutonium bearing laundry waste, in a mixture with settled domestic sewage, was treated by the activated sludge process by Reading and co-workers (38). Using 20-liter bottles as aeration units, they found good removal with long aeration periods followed by filtration of the effluent. They also observed a high concentration of plutonium in the zoogleal mass of sludge even when the raw feed was low in radioactivity. This would necessitate special handling of the excess sludge.

Eden et al. (39), in their laboratory scale investigation of activated sludge, found that equilibrium between the activities of the liquid and solid phases was reached after 16 hours aeration. They obtained removals of 95 per cent for plutonium-239, 89 per cent for iodine-131, 42 per cent for strontium-90 and ruthenium-106, and 32 per cent for cesium-134.

In studying the efficiency of sand filters for removing low-level activity from laboratory wastes, Gemmell (40) observed 98 per cent removal of the activity for the first 16 dosings (4 days), 70 per cent removal for the next 10 dosings (2 1/2 days) and only 20 per cent after 37 dosings (9 days). Of the activity absorbed in the bed, 90 per cent was found in the top 3 inches, 8 per cent in the next 9 inches and the remaining 2 per cent was located in the lower 5 feet.

Eden et al. (39), using slow sand filters on the laboratory scale, found that plutonium-239 and cerium-144 were effectively removed but iodine-131, strontium-90, and ruthenium-106 experienced a rapidly decreasing removal efficiency with increased dosing.

Evaluation of the effectiveness of oxidation ponds (lagoons) on the removal of various radionuclides, has also been the object of investigations on the laboratory scale. Steel and Gloyna (41, 42) found that iodine-131 was not removed to any great extent but appreciable removal of mixed fission products was experienced. The removal of phosphorus-32 and strontium-89 was found to be dependent upon the concentration of stable counterparts and chemically similar isotopes.

Gloyna et al. (43), in their experimental work, obtained very low removals of cesium-137 and iodine-131; however, they did find that

35 per cent of the applied strontium-89 could be removed by a single laboratory lagoon and up to 80 per cent could be removed by three lagoons in series. Mixed fission products were found to collect in the slime and sludge with slow release back to the liquid phase. It was found that the algae, under optimum conditions of light, temperature, pH and nutrients, could remove as much as 95 per cent of the influent cerium-141.

Herman and Gloyna (44), in summarizing the investigations on the removal of radioisotopes by oxidation ponds, reached the following general conclusions.

1. Oxidation ponds can be used effectively to concentrate, delay and, possibly, remove radioisotopes from waste streams especially when the concentration of radioactivity is near the maximum permissible concentration (MPC).
2. Intermittent slugs of low-level amounts of radioisotopes can be diluted and, in many cases, removed by the long detention times utilized in oxidation ponds.
3. Where climatic conditions are favorable, oxidation ponds can be economical both as a BOD reduction device and for treating low-level radioactive wastes.

CHAPTER III

PURPOSE AND SCOPE

The literature seems to indicate that appreciable work has been done in the general area of the removal of radioisotopes by sewage treatment processes. However, upon closer inspection it is apparent that, for the most part, this work was carried out on a laboratory scale under exactly controlled conditions and only a few isotopes were used in investigating a single phase of treatment. In most cases laundry waste, or a synthetic waste of some type, was used as the vehicle. In a sizable portion of these studies, interest was centered on the effects of the radioisotopes on the treatment process rather than the action of the treatment process in removing the radioisotopes from the waste stream. Careful inspection of the experimental results shows that, in some cases, appreciable disagreements and even contradictory conclusions have resulted from similar investigations. One case in point is the ability of trickling filters to remove iodine-131. Carter (26) reported a removal efficiency of 85 per cent while the value recorded by Belcher (23) was only 5 per cent.

Unfortunately, conditions developed in the laboratory using small scale units operating under completely controlled conditions are incompatible with conditions prevailing in the field. Such laboratory results may be valid for indicating general trends or for comparison purposes but they can be grossly misleading when projected to large-scale

field operations. There are probably few other fields of science where these statements hold more truth than in the field of waste treatment.

The prevalence of laboratory investigations of the various aspects of biological treatment of radioactive wastes and the virtual nonexistence of their large scale counterparts, has been noted (45). As pointed out previously, the sewage treatment plant is rapidly becoming the focal point for the disposal of practically all of the low-level radioactive wastes from our urban activities. In view of this, there is a pressing need for initial pilot scale research utilizing an entire sewage treatment plant operating under true field conditions free from the inherent inadequacies of laboratory scale research and synthetic wastes. It was this need that provided the purpose for this investigation.

More specifically, the purpose of this investigation was to render an evaluation of the effects of a complete sewage treatment plant operating under actual field conditions on sewage that has been contaminated with a representative spectrum of radioisotopes in low-level amounts. Of primary interest was not only the fate of the radioisotopes but also the underlying procedures responsible for their removal.

To achieve this goal, a pilot size sewage treatment plant employing a standard rate trickling filter and a lagoon was utilized. In order to facilitate the investigation on this scale and to comply with the restrictions on the use of radioactive materials and the discharge of the resulting wastes to the receiving streams, it was decided that this study be conducted with relatively short half-life radioisotopes. This, however, in no way limits the scope of this investigation since numerous such radioisotopes, representing practically the entire range of

radionuclides, are readily obtainable. The radioisotopes selected were not only representative of the periodic table but also representative of the significant fission products as well as being among those considered most biologically hazardous.

The radionuclides chosen, along with some of their more important characteristics, are listed in Table 1. In this tabulation, the information concerning maximum permissible concentrations and critical organs was obtained from the Federal Register (46), Handbook 69 (13), and Radiation Monitoring (47). Data concerning the other characteristics were obtained from the Radiological Health Handbook (48).

TABLE 1

CHARACTERISTICS OF SELECTED RADIONUCLIDES

Radio-nuclide	Half-life	Type of Radiation, Energy in Mev. and Percentage of Disintegrations in which a Particular Radiation Is Emitted	Daughter	Fission Yield in %	MPC[a] (μc/cc)	Critical Organ(s)
P-32	14.5 days	Beta 1.71 (100%) Gamma None	Stable	--	2×10^{-5}	Bone
I-131	8.05 days	Beta 0.81 (0.7%), 0.61 (87.2%) 0.33 (9.3%), 0.25 (2.8%) Gamma 0.36 (80%), others	Stable	2.9	2×10^{-6}	Thyroid
K-42	12.5 hrs.	Beta 3.55 (82%), 2.0 (18%) Gamma 1.51 (18%)	Stable	--	2×10^{-5}	Gastrointestinal Tract
Ce-141[b]	32 days	Beta 0.58 (30%), 0.44 (70%) Gamma 0.14 (30%)	Stable	5.7	9×10^{-5}	Gastrointestinal Tract, Liver and Bone
Ce-144[b]	285 days	Beta 0.31 (70%), 0.25 (5%) 0.17 (25%) Gamma 0.08, 0.05, 0.13	Pr-144	6.0	1×10^{-5}	Gastrointestinal Tract, Liver and Bone

[a]Maximum permissible concentrations in water for 168 hours per week occupational exposure.

[b]Ce-141 was unavailable in the quantity desired; consequently, a mixture composed of 89 per cent Ce-144 and 11 per cent Ce-141 was used.

TABLE 1 -- (Continued)

Radio-nuclide	Half-life	Type of Radiation, Energy in Mev. and Percentage of Disintegrations in which a Particular Radiation Is Emitted		Daughter	Fission Yield in %	MPC[a] (μc/cc)	Critical Organ(s)
Fe-59	45 days	Beta	0.27 (46%), 0.46 (54%) 1.56 (0.3%)	Stable	--	6×10^{-5}	Gastrointestinal Tract and Spleen
		Gamma	0.19 (2.8%), 1.10 (57%) 1.30 (43%)				
Co-58	71 days	$Beta^{+}$	0.48 (15%)	Stable	--	9×10^{-5}	Gastrointestinal Tract and Total Body
		Gamma	0.80 (99%), 1.66 (0.5%) 0.86 (1.6%)				
Sr-89	54 days	Beta	1.46 (99+%), 0.54 (0.01%)	Stable	4.5	10^{-5}	Bone
		Gamma	0.91 (0.01%)				
MFP	45 days	Beta	Several	--	--	10^{-6}	--
		Gamma	Several				

[a]Maximum permissible concentration in water for 168 hours per week occupational exposure.

CHAPTER IV

DESCRIPTION OF EXPERIMENTAL UNITS

Introduction

All experimental units and laboratory facilities used in this investigation are located at the Earle B. Phelps Laboratory for Sanitary Engineering Research at the University of Florida at Gainesville. This laboratory is not only active in waste treatment research but also in environmental radiation surveillance and the teaching of sanitary science. At present the pilot sewage treatment plant, operated by the staff of this laboratory, consists of a primary sedimentation basin, an Imhoff tank, an extended aeration unit, two trickling filters, numerous sand filters, two sludge digesters and a lagoon. These units are arranged so that they can be operated independently or in practically any conceivable series and under a wide range of loading conditions. Collectively, they have a treatment capacity of approximately 60,000 gallons per day. For [illegible] it was decided to employ those units [illegible] pilot plant under standard loading rates.

The sewage is received at the research laboratory's pilot plant from the University of Florida campus and included drainage from dormitories, classroom and laboratory buildings, cafeterias, family housing units, fraternities, sororities, a milk processing plant, and the J. Hillis Miller Health Center. It is received at the pilot plant

at a uniform rate from the campus sewage treatment plant after it has been screened, comminuted, and degritted. As expected, the strength of the sewage was found to vary markedly throughout the day and also throughout the week. Because of the short flow time in the mains, the sewage reaching the plant was normally fresh.

Primary Sedimentation Basin

The function of a primary sedimentation basin is to provide, in the initial phases of sewage treatment, a relatively quiescent state so that those suspended particles having a higher specific gravity than the liquid phase will settle under the influence of gravity. Thus, the primary purpose of such a unit is to reduce the solids load on succeeding treatment processes thereby increasing the treatment efficiency while reducing maintenance. Most sedimentation basins are designed on a continuous flow basis and are equipped with any one of a variety of sludge collection and removal devices. Under normal loading rates, such treatment units can remove 50 per cent of the influent suspended solids and 35 per cent of the applied BOD.

The basin employed in this investigation (Figure 1) is rectangular
The settling compartment is 12 feet in length, 4 feet in both width and
an influent distribution box as well as influent and effluent baffles.
The settling compartment is 12 feet in length, 4 feet in both width and depth and has a free-board of 1 foot. The effluent from this compartment flows over a 4-foot long notched weir which leads to a collection trough. From here it enters a 4-inch diameter pipe leading to an outfall in a reinforced concrete dosing tank. It was at this outfall that the primary effluent samples were taken.

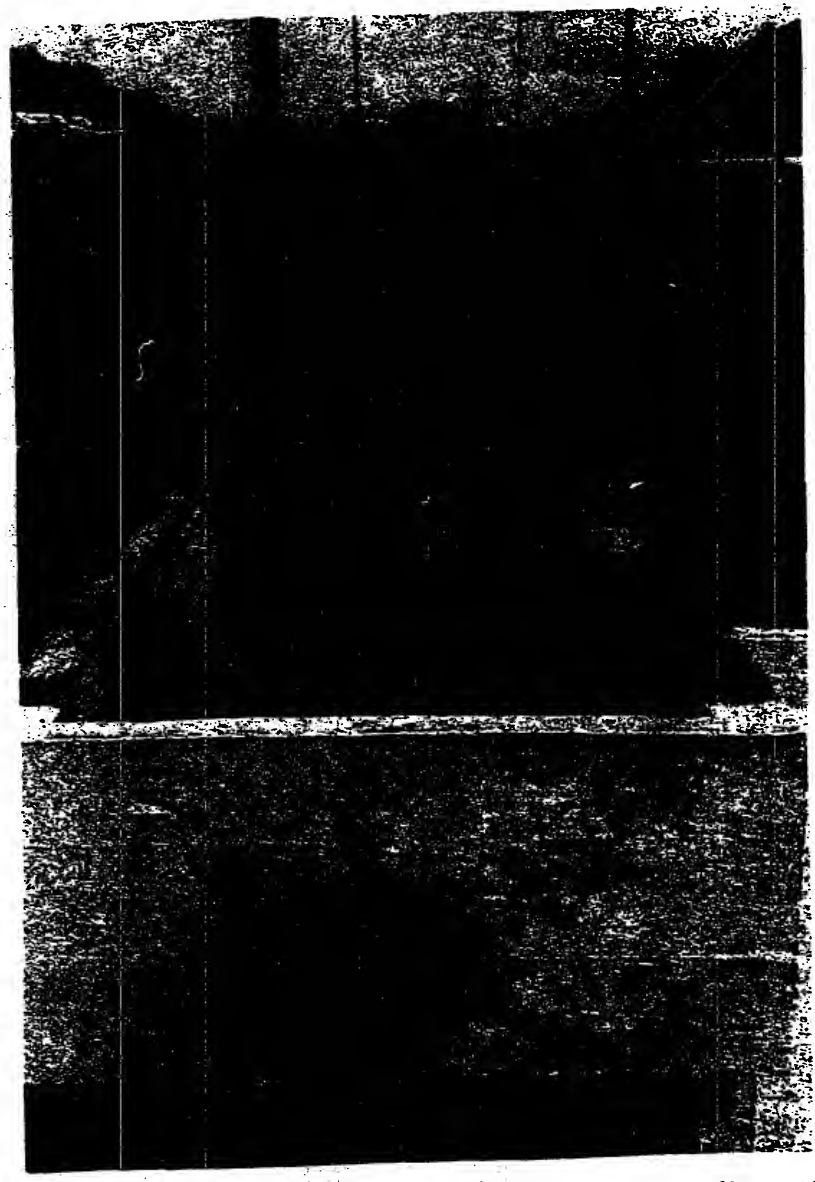


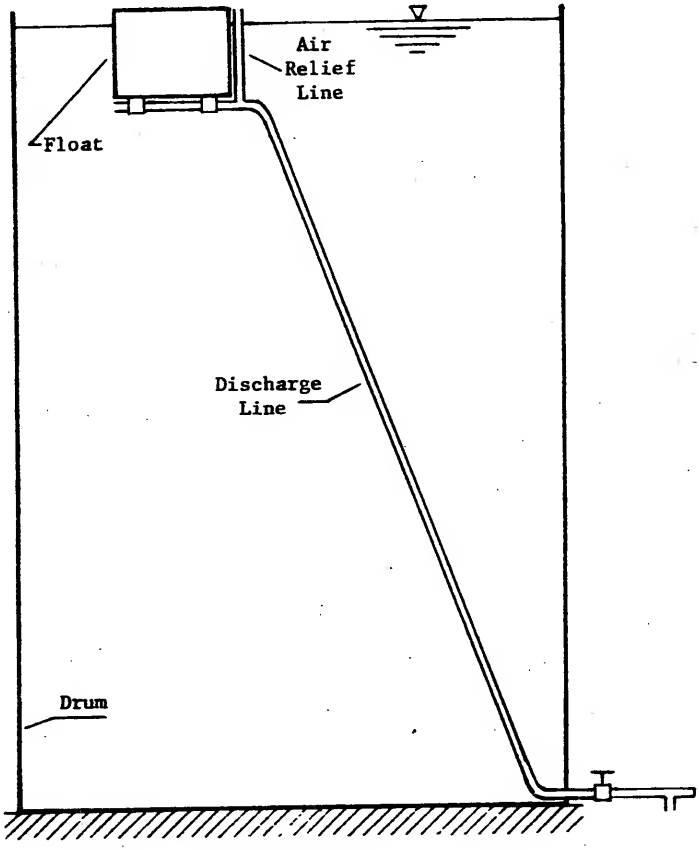
Fig. 1.- General view of the experimental primary sedimentation basin.

The unit is equipped with two sludge collection hoppers having a combined capacity of 338 gallons thus giving the basin a total capacity of 1,778 gallons. For the course of this investigation, this unit received sewage at the approximate rate of 15 gallons per minute. Calculations yield a theoretical detention time of 96 minutes, a surface loading rate of 450 gallons per square foot per day and a theoretical horizontal velocity of 1/10 of a foot per minute.

Withdrawal of sludge is accomplished by means of a hydrostatic pressure of 3 feet. The withdrawal pipes are 4 inches in diameter with the flow controlled by shear gates located in receiving hoppers adjacent to the unit.

The dosing device (Figure 2) used in the application of radioisotopes to this unit was composed of a 55-gallon steel drum equipped with a polyvinyl chloride discharge line attached to the bottom of a weighted float. The latter, which was 5 inches in diameter by 3 1/2 inches deep, projected 1/2 inch above the surface of the liquid in the drum, thus providing a constant hydraulic head of 3 inches above the intake of the discharge line. The discharge line itself was 1/4 inch in diameter and 3 1/2 feet long with its lower end attached to a 1/4-inch diameter valve which passed through the wall of the drum, flush with the bottom.

The discharge of the apparatus as described above would be a function of the depth of the liquid in the drum. In order to eliminate this dependency, an air relief line was placed in the discharge line 5 inches down stream from the intake. This line was composed of a short piece of 1/4-inch diameter polyvinyl chloride tubing connected to the discharge line through a glass "T" and projected vertically through the surface of the liquid.



Scale: 1" = 6"

Fig. 2.- Sectional view of the primary sedimentation basin isotopic dosing device.

This apparatus was calibrated to deliver a uniform discharge of 1 quart per minute over a span of 45 gallons, starting with the drum full and continuing to within 6 inches of the bottom. The solution containing the radioisotopes was added to the basin influent as it entered the distribution box at the head of the unit. The thorough mixing occurring at this point insured a complete distribution of the isotopic solution throughout the incoming sewage before it entered the sedimentation zone of the unit.

In order to facilitate the dosing and representative sampling of both the primary sedimentation basin and the trickling filter and to prevent the radioisotopes in the settling tank effluent from entering the other units before they could be systematically investigated, it was decided to operate the primary sedimentation basin on a line independent of the other units being investigated.

Standard Rate Trickling Filter

Trickling filters are applicable for secondary treatment of wastes susceptible to aerobic biological processes. They have been used with success on domestic sewage, industrial wastes and mixtures of industrial and domestic wastes. They have the ability to recover from shock and toxic loads and to provide good performance with a minimum of skilled technical supervision. Probably no other biological treatment process is so versatile in its application or so dependable in its performance.

These units are normally 6 to 8 feet deep and have stone medium 2 to 4 inches in diameter. They are commonly round in plan and have some type of rotary distribution for applying the sewage to the surface

of the bed. Collection of the treated effluent requires an under-drain system which, due to frequent sloughing of solid material from the filter, usually leads to a secondary sedimentation basin. Standard rate trickling filters receive hydraulic loadings of 1 to 4 million gallons per acre per day and under normal conditions, a 6-foot filter should remove 80 to 85 per cent of the applied BOD.

The action occurring in such a unit can be described briefly as the biochemical sorption of the complex organic matter present in sewage, carried out by allowing the sewage to come in contact with the microorganisms active in its degradation. The means of contact is usually provided by the distribution of primary treated sewage over the top of a unit containing a coarse medium, the surface of which is coated with a viscous jelly-like matrix of microorganisms called zoogleal slimes. As the sewage trickles down through the bed, it passes over the surfaces of these slimes in a relatively thin film. It is here that the colloidal and dissolved organic matter is removed from the liquid phase, used as a source of energy by the biota in the slimes and replaced in the liquid phase by their stable metabolic products.

It is appropriate that the underlying theory of the stabilization of organic matter by trickling filters should be presented at this point, especially since it is expected that this theory will find considerable application in discussing the ability of a filter to remove radioisotopes.

The early theories concerning the phenomenon of purification by trickling filters were generally based on the process of absorption. In the light of later developments in the chemistry of colloids, the true mechanism appears to be that of adsorption. Based on this premise,

Buswell (49, 50) developed a more comprehensive theory explaining the action of these units. His work, which represents the presently accepted theory, has been summarized by Metcalf and Eddy (51) and by Fair and Geyer (52) as follows:

"1. In the surface film of liquids, the concentration of dissolved matter tends to change in such a way as to decrease surface tension. If, therefore, a substance dissolving in a liquid increases the surface tension of the solution, the film concentration of the substance tends to become less; if it decreases the surface tension, its film concentration tends to become greater. (Most salts and all strong bases increase the surface tension of water; but, ammonia and nitric and hydrochloric acids decrease it.) Substances in the colloidal state are believed to act in a similar way and there are found in sewage colloidal soaps and proteins that tend to concentrate in a surface film. These changes in film concentration are not restricted to the air-liquid interface, but seem to apply also to the interface between the bacterial slime and the liquid. The extent of the interface or contact surface is, therefore, important.

"2. At the jelly-sewage interface the following occurs:

a) The substances concentrating at the interface are adsorbed to the contact surfaces and thus removed from the sewage being filtered;

b) The adsorbed substances are attacked by the enzymes and living organisms present in the slime;

c) As rapidly as these substances are removed by digestion or direct absorption into the living cells, others come to the interface and further removal is effected;

d) In the presence of air, the products of decomposition of organic matter are chiefly carbon dioxide, nitrates, and a humus-like residue. The gas escapes . . . nitrates, being salts, increase the surface tension of water and therefore pass from the interface into the flowing sewage; the humus-like residue must either be removed . . . or sloughed off from time to time . . . . It is an important fact that the humus . . . settles readily, unlike the colloidal matter from which it largely originated."

This summary omits a very important hypothesis that was proposed by Buswell. This hypothesis was that the rate of purification is directly related to the law of mass action. Simply, this law states that the rate at which a reaction occurs is in direct and constant proportion to the concentration of the reactants. Incorporation of this law into the above summary yields the presently accepted theory of trickling filter operation.

In summary, the action of a trickling filter can be described as follows: removal of colloidal and dissolved material by adsorption on the zoogleal surfaces; oxidation of the organic material by the biota which constitutes the zoogleal mass; resolution and sloughing of the oxidized material and its passing from the filter. The removal of organic material by adsorption on the bacterial jelly seems to be a concentration phenomenon, with the rates of removal and oxidation being dependent on the rate of oxygen transfer, temperature and the surface area involved.

The filter used in this study is 8-feet deep and has an inside diameter of 6 1/2 feet, thus giving a surface area of 33 18/100 square

feet and a medium volume of 9 6/10 cubic yards. The filter tank is constructed of 3/8-inch steel plates, circular in plan, with a sloping concrete bottom covered with formed tile under-drains which lead to a 4-inch diameter effluent line. This line outfalls into a 12-inch diameter semi-circular trough leading to the secondary sedimentation basin.

The sampling ports consist of short 6-inch diameter nipples, which are welded to the steel shell of the filter. There are 16 of these nipples, which are aligned in pairs in order to support, on the inside of the filter, two facing 4-inch steel channels separated by 3/4 of an inch and extending across the filter. These channels have triangular shaped cuts in their flanges to facilitate the passage of sewage. They are positioned so as to form a 3 1/2-inch by 3 1/2-inch opening through which liquid and slime samples may be taken without being obstructed by the medium. Each port has a small metal bar welded horizontally across the middle of the opening. Each pair of bars supports a flattened 1-inch diameter aluminum conduit cut the length of the channel and used for mounting the glass slides employed in sampling the filter slimes. Sampling ports are located at the 1/2 and 1 foot depths and at each foot thereafter for a total depth of 7 feet. The samples representing the 8-foot depth are taken at the point where the filter effluent empties into the secondary influent trough. In order to prevent short-circuiting of the sewage as it passes through the filter, all channels are placed in different vertical planes.

Liquid samples were collected at the various sampling ports by means of aluminum sampling troughs, which are semi-circular in shape,

3 inches wide and 8 feet long. At one end of the trough is an outlet nipple onto which a length of 3/4-inch diameter garden hose is connected to allow the continuous filling of the 600-milliliter beakers in which the samples were collected. A general view of the filter showing the ports and the equipment used in sampling appears in Figure 3.

The medium used in the experimental filter is a native limerock furnished to the University of Florida by the West Coast Rock Company of Fort Myers, Florida.[a] These heavy and fairly uniform stones have an average size of 4 inches, which exceeds the maximum value given in the "Sewerage Guide" of the Florida State Board of Health. The stones have porous and irregular surfaces that provide an excellent foundation for the growth of the zoogleal slimes. In order to prevent the formation of open pockets under the channels, to hold settling to a minimum and to insure even distribution of sewage throughout the filter, the medium was hand-placed. This limerock is performing excellently as a filter medium and has shown no evidence of settling or deterioration after almost 5 years of use.

The sewage being treated by this unit receives primary sedimentation in an Imhoff tank before being discharged into a large reinforced concrete receiving tank. From here the sewage is pumped at a constant rate by a centrifugal pump to an elevated dosing chamber. Part of the flow coming into this chamber flows over an adjustable weir into a bell siphon chamber, the head on this weir being kept constant by two large overflows that return the excess sewage to the receiving tank.

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[a]A complete chemical analysis of this material appears in Appendix A.

Fig. 3.- General view of the experimental trickling filter.

The sewage is then siphoned to a distribution box from which it flows over a series of adjustable weirs, one of which leads to the filter being investigated. Mechanically driven rotary distribution arms operating at a rotation rate of 1 revolution per minute provide a uniform distribution of the sewage over the filter medium.

For the course of this investigation, the bell siphon cycle was maintained at a constant 7 3/4 minutes which was divided into a 2 3/4-minute dosing period and a 5-minute resting period. The distribution weir was adjusted to send approximately 17 gallons per cycle to the filter. This corresponds to a hydraulic loading rate of 4 1/10 million gallons per acre per day.

The device used in the application of radioisotopes to the influent of this unit was basically composed of a float switch, a Sigma Motor pump and a holding tank. The float switch was mounted on a vertical support bolted to the wall of the bell siphon chamber and the float was allowed to fluctuate with the liquid level in this chamber. The pump, powered by a 1/20-horsepower electric motor operating through a gear box, was housed on a platform over the distribution weirs. The holding tank, which was located adjacent to the pump housing, was constructed from a 14-gallon polyethylene carboy equipped with a bottom drain connected to a 3/16-inch diameter rubber tube. The shielding for this container was provided by a 1/8-inch thick steel tank, 15 inches in diameter by 30 inches deep and equipped with a twist-lock lid. The rubber tubing connected to the bottom of the carboy projected through the bottom of the steel tank, extended through the pump, and terminated on the down-stream side of the weir which dosed the filter. The arrangement of these units is shown in Figure 4.

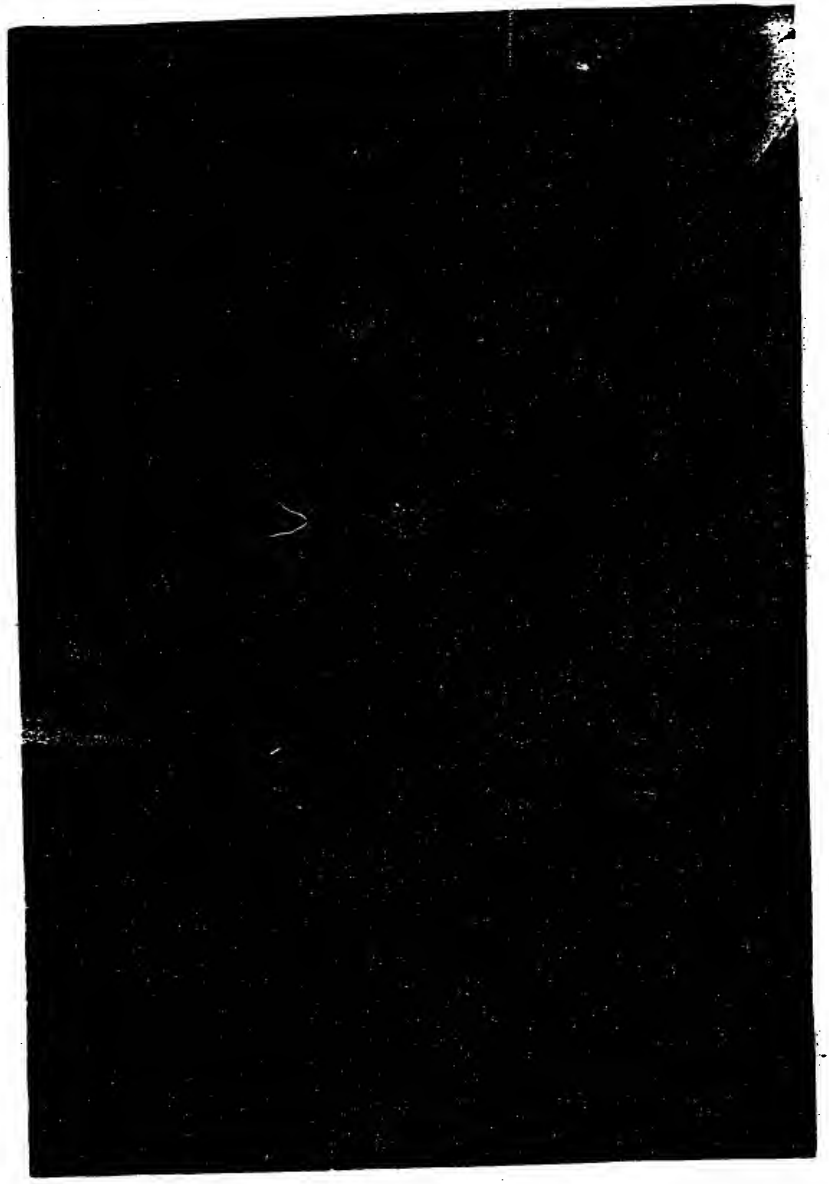

Fig. 4.- Dosing devices used in the application of sewage and radioisotopes to the experimental trickling filter.

As the level of the sewage in the siphon chamber rose to the point at which dosing started, a stop on the float staff, acting through the float switch, started the electric motor which operated the pump. The latter pumped the isotopic solution from the holding tank to the sewage being sent to the filter. The turbulence provided by the drop from the weir to the filter influent line along with the mixing occurring in the influent line and the distributor arm nozzles, provided a complete distribution of the isotopes throughout the sewage. As the level of the sewage in the siphon chamber dropped to the point where the siphon was broken, a second stop on the float staff switched off the pump.

This dosing device was calibrated to deliver approximately 350 milliliters of isotopic solution per dosing cycle. Under the installation and operating conditions used, the discharge of the pump was independent of the liquid level in the holding tank.

The device described above permitted the application of a fairly small but reasonably uniform dose of radioisotopes to only that portion of the sewage going to the unit under investigation and only during that part of the cycle that the unit was actually receiving sewage. The transfer of the isotopic solution from the holding tank to the sewage was carried out with an externally applied pumping device operating on a completely closed system equipped with readily accessible and easily replaced component parts.

Secondary Sedimentation Basin

The function of secondary settling tanks and the basic principles by which they operate are practically identical to those of primary

settling tanks. Generally, design criteria for sedimentation tanks apply equally well to both types of basins. The principal difference between the two units is the type of suspended solids encountered.

The effluent from trickling filters contains large quantities of settleable organic matter, particularly when the filter is undergoing the process of "unloading." This material is more putrescible, has a higher oxygen demand and is lighter and more flocculent than the sludge from primary tanks. Generally, sedimentation of the filter effluent to remove this material is required; consequently, secondary sedimentation is commonly considered part of the over-all process of stabilization by trickling filters. As a result of this, treatment criteria for this unit are usually integrated into a single set of values for the complete process.

The secondary sedimentation basin used in this investigation was constructed from a section of precast concrete pipe 5 feet in diameter and 4 feet long. The sedimentation zone has a liquid depth of 2 feet and a free board of 6 inches, the latter being provided by the bell of the pipe. Sludge collection is carried out in a conical shaped hopper that accounts for the lower 2 feet of the basin. The trickling filter effluent enters the unit through a 4-inch diameter pipe which passes through the sedimentation zone to the center of the basin where it empties into a 12-inch diameter down-draft tube that acts as a submerged inlet and an influent baffle. From here the liquid rises up through the sedimentation zone and over an annular overflow weir which is 2 feet in diameter and concentric with the down-draft tube. The secondary effluent is then collected in a channel behind the weir and allowed to

leave the basin through a 4-inch diameter pipe. The unit is equipped with a pump for sludge removal and has a theoretical detention time of 2 hours in the sedimentation zone.

In accordance with the concept that the secondary settling tank is part of the trickling filter process, this unit was investigated in conjunction with the filter. Both units were dosed simultaneously and sampled concurrently. The radioisotopes reaching the settling tank during any one dose were the same ones leaving the filter during the same dose with no additional activity being added and with no operational changes. In this manner both mutually dependent units were investigated without violating the unity of the process or the continuity of treatment.

Lagoon

Lagoons or stabilization ponds are relatively shallow basins built for purposes of treating raw, primary or secondary wastes by storage under conditions that favor natural biological treatment and accompanying bacterial reduction. When used to treat secondary effluent, as was the case in this investigation, they are frequently called "polishing ponds" -- the name arising from the fact that they provide the finishing treatment in cases where a high degree of stabilization is desired before the effluent is discharged to the receiving stream. Used in this capacity, they can furnish an effluent having a low BOD and coliform bacterial content and a dissolved oxygen content often in excess of saturation.

The unit used in this investigation (Figure 5) has an effective length of 23 1/2 feet and an effective width of 12 feet. It is of

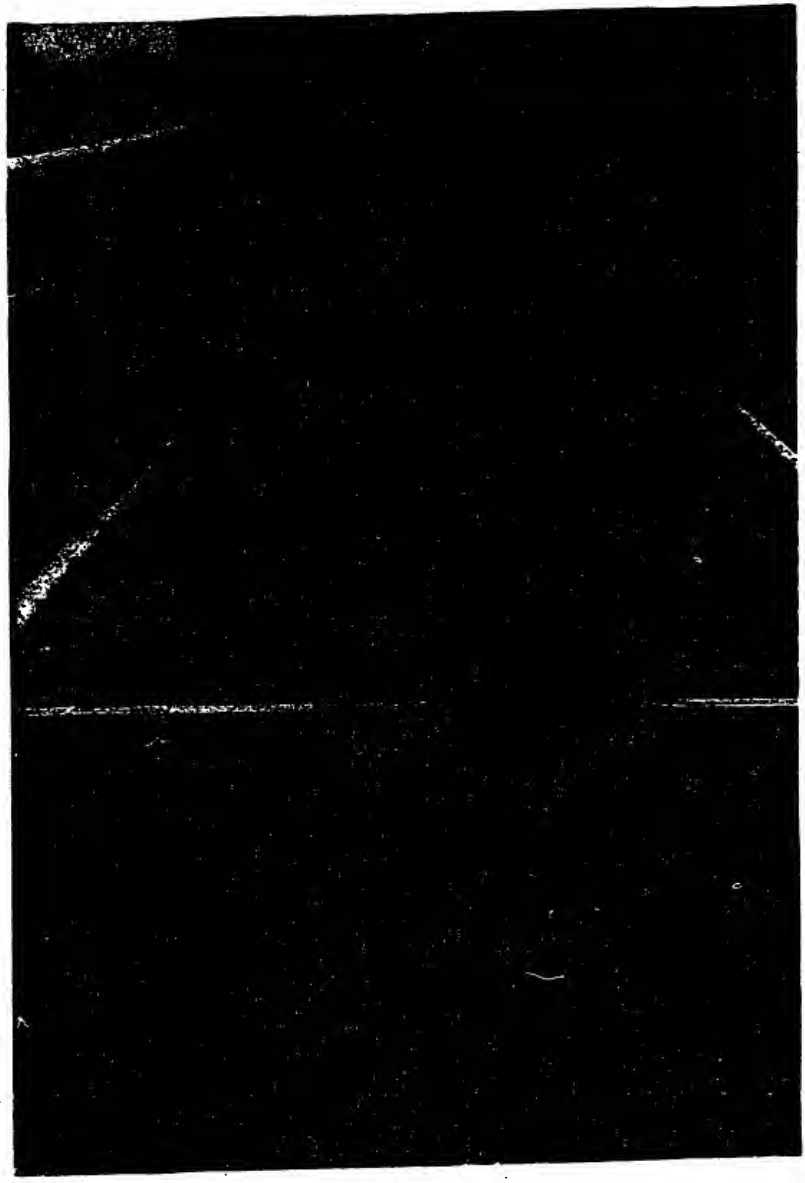

Fig. 5.- General view of the experimental lagoon.

masonry construction with 19 equally spaced around-the-end baffles, each 11 feet long and turned width-wise in the basin. Essentially, this forms a channel 1 foot wide, 2 feet deep and over 200 feet long.

A Moyno worm-type pump supplied secondary effluent to this unit through a 1-inch diameter line, the intake of which was located just in front of the effluent weir of the secondary sedimentation basin. By use of a timer, the 3/4-horsepower electric motor that operated the pump was allowed to run 1 minute out of every 3. This gave the lagoon an average influent of 1/2 of a gallon per minute which corresponds to a theoretical detention time of 4 3/4 days. To prevent back-siphoning through the pump and to provide a representative influent sampling point, an air gap was provided between the influent line and the surface of the liquid in the influent channel of the lagoon. Control of the liquid level in this basin was provided by a V-notch weir at the effluent end. This weir also functioned as the effluent sampling point.

In keeping with the role of this unit as a polishing device, it was decided that no additional isotopes would be added to the influent of this basin. True field conditions dictate that not only the amount but also the physical and chemical characteristics of the isotopes in the influent of this unit be identical to those in the effluent of the secondary sedimentation basin.

Since the primary and secondary units used in this investigation were operated on two separate lines with each line being dosed at different times, only half of the total flow through this portion of the pilot plant was contaminated with radioisotopes at any one time. This gave an isotopic dilution factor of 1 to 1 when these two flows

were combined. An additional dilution of 1 to 1 was obtained when this combined flow was added to the effluent from the other units of the pilot plant. The effluent from the entire pilot plant was then allowed to enter an underground conduit where it was diluted with surface drainage having a dry weather flow in excess of 80,000 gallons per day. The addition of the effluent from the campus sewage treatment plant to this stream resulted in a further dilution of 10 to 1. Thus, the effluents from the units under investigation were diluted to less than 1 part in 80 before being discharged to a 1-acre restricted use pond. This dilution factor plus the use of short half-life radioisotopes in low-level amounts, prevented the development of any radiation hazards even if there had been no removal or buffering action by the units under investigation.

CHAPTER V

PROCEDURE

The radioactive materials used in this investigation were arranged in eight experiments with three replications each. Six of these experiments were concerned with individual radioisotopes, one experiment was carried out with a mixture of two isotopes of radio-cerium and the final experiment was conducted using mixed fission products. In order to minimize the accumulation of activity within the treatment units, these materials were arranged for investigation in order of increasing physical half-life; however, the chemical characteristics of some of the selected radionuclides precluded rigid adherence to this scheme and minor modifications were required. The materials used, the order of their application, their chemical form and influent concentrations are shown in Table 2.

In order to determine the proper dosing duration, the location of representative sampling points and an adequate sampling frequency for each unit and to evolve a systematic sample processing procedure, an intensified and extended sampling program was conducted during the initial run of the first experiment. The results of this preliminary study indicated that equilibrium of the effluent activity was reached within 2 hours in the primary sedimentation basin, within 12 hours in the trickling filter and secondary sedimentation basin and within 6 days in the lagoon. On the basis of this information, a week was allowed

TABLE 2

RADIONUCLIDE DOSING DATA

Experiment	Radionuclide	Chemical Form[a]	Approximate Influent Concentrations[b] (pc/ml)
1	P-32	$PO_4^{\equiv}$ in dilute HCl	10 - 80
2	I-131	I^- in basic Na_2SO_3	20
3	K-42	KCl in dilute HCl	10 - 200
4	Ce-141,144	$CeCl_3$ in dilute HCl	100
5	Fe-59	$FeCl_3$ in dilute HCl	30
6	Co-58	$CoCl_2$ in dilute HCl	45
7	Sr-89	$SrCl_2$ in dilute HCl	100
8	MFP	Nitrates in dilute HNO_3	50

[a]For dosing purposes, all radioisotopes were diluted with tap water and the pH was adjusted to correspond to that of the original solution.

[b]Calculations expressing the influent concentrations in milligrams per liter are illustrated in Appendix B.

for each of the three replications of each experiment and an additional week of normal operation was provided between experiments in order to substantially eliminate the preceding radioactive materials from the treatment units. The detailed sampling procedures applied to the individual units are outlined in the following sections.

Primary Sedimentation Basin

Immediately preceding each run, influent flow measurements were made, influent and effluent background samples were taken and the dosing solution was prepared and assayed. After dosing started, effluent samples for radiological analysis were taken every 5 minutes for the first 30 minutes then at 10-minute intervals for the next 2 1/2 hours.

Trickling Filter

Six days prior to the start of each run, six glass slides were attached to each of the eight holding plates which were then inserted into their respective sampling ports. Immediately preceding each run, three of these slides from each port were removed, allowed to drain well and the accumulated biological growth was transferred to 100-milliliter beakers with the aid of a clean rubber policeman and 4 milliliters of distilled water.

Liquid samples for radiological analysis were taken from the filter influent, the 2-, 4-, and 6-foot ports and the filter effluent at time zero and at the end of 2, 4, 8, 12, and 24 hours of isotopic dosing. At this time, the three glass slides remaining in each of the eight sampling ports were removed and processed as described above. All preliminary liquid samples were 600 milliliters in volume and in order to eliminate any variations between individual doses, these samples were all collected during the same dosing cycle. Proper evaluation of the filter per se required the removal of the settleable material from all liquid samples taken from the various ports. This was accomplished by providing the preliminary samples with 1 hour of quiescent sedimentation before the final samples were decanted into 100-milliliter beakers.

Secondary Sedimentation Basin

Liquid samples for radiological analysis were taken from the influent and effluent of this unit at time zero and after 2, 4, 8, 12, and 24 hours of filter dosing. Representative samples of secondary

sludge for each of these times were obtained by allowing 600 milliliters of the basin influent to undergo quiescent settling for 1 hour. At this time, 3 milliliters of the settled material were removed with a dropper and transferred to a 100-milliliter beaker.

Lagoon

The long detention time and buffering capacity of this unit permitted a less intensified sampling frequency but required an extended sampling duration. It was found that the action of this unit could be adequately described by taking influent and effluent samples for radiological analysis every 24 hours starting simultaneously with the filter dosing and continuing for 6 days.

Sample Preparation

All liquid samples except for those from experiments 2 and 3 were prepared for counting by the following method. After obtaining the samples as described above, 50 milliliters of each were transferred with a graduated cylinder to clean 100-milliliter beakers and allowed to evaporate to dryness in a 103° C forced-air drying oven. The residue obtained was transferred from the beakers onto planchets by successive washing and scrubbing with a clean rubber policeman and distilled water. Two drops of 2N hydrochloric acid were added to the first of the four wash waters. The residue on each planchet was then evaporated to dryness under heat lamps.

All sludge and slime samples except for those from Experiment 2 were prepared for counting by transferring the samples directly to dried and tared planchets and evaporating them to dryness under heat lamps.

After counting, these planchets were stored in a desiccator for at least 12 hours before the final weights were taken.

The instability of iodine in acid or weakly basic solutions at elevated temperatures required modification of the sample drying procedure. For this experiment, all liquid samples were made basic to phenophtalein with 2N sodium hydroxide before being placed in the 103° C oven. After drying, the residues were transferred from the beakers to the planchets by normal washing procedures, omitting the 2N acid in the first wash. The planchets were then allowed to evaporate to dryness in a 70° C oven before counting. The sludge and slime samples for this experiment were collected in the previously described manner, made basic by the addition of two drops of 1/20N sodium hydroxide and transferred to the pre-weighed planchets. They were then dried at 70° C and counted by the normal procedure.

The short half-life of potassium-42 (Experiment 3) necessitated the elimination of the lengthy evaporation time required by the liquid samples before their residue could be transferred. It was found that two half-lives could be saved between the sampling and counting stages by transferring exactly 4 milliliters of each sample directly to their respective planchets and evaporating them under the heat lamps. Even though low count rates were obtained with these small samples, the reproducibility obtained by this method was as good as that which would have been obtained by the normal method and only 1/4 the quantity of isotopes was required.

Counting Technique

For Experiment 1 all samples were placed on copper planchets having a sample deposit area of 8 square centimeters and subjected to gross counting in a Nuclear-Chicago automatic counting system having an efficiency of 35 per cent for thallium-204. This counting sequence was composed of an end window proportional counter, a Model C-110 B sample changer and a Model 186 scaler. The counter was operated at 2150 volts and supplied with "PR" counting gas under slight pressure. For the most part, this system was operated on a pre-set count mode with the counting times being recorded on a Model C-111 B printing timer.

Prior to Experiment 2, a Baird-Atomic automatic counting system became operational and since it allowed considerable flexibility in operation, it was used for this and all subsequent experiments. This system, which had an efficiency of 40 per cent for thallium-204, consisted of a Model A-227 gas flow end window proportional counter, a Model 750 sample changer and a Model 132 scaler. All samples were prepared on stainless steel planchets 5 centimeters in diameter and subjected to gross counting at 2050 volts using "PR" counting gas supplied under low pressure. This system was also operated on a pre-set count basis and the counting times were recorded on a Clary print-out timer.

In order to eliminate as much counting variability as possible, all samples taken from the same treatment unit and having related sampling times were grouped into sets and counted during the same counting sequence. All samples were counted at least twice with a background determination included in each counting run. For purposes

of assessing the normality of operation of the instrumentation, no less than two uranium standards were included in each counting operation.

Since all samples from the same experiment were placed on the same type and size planchet and counted on the same instrument, no corrections for geometry or backscatter were necessary. The use of a systematic handling procedure and relative counting techniques eliminated the need for all counting corrections except background and decay, the latter being required for Experiment 3 only.

The activity of all liquid samples was reported in counts per minute per 50 milliliters with the exception of the corresponding data from Experiment 3 which were based on a sample volume of 4 milliliters. To gain maximum reproducibility and minimum variability, the activity of all sludge and slime samples was reported in counts per minute per milligram of dry solids.

Both counting systems could be operated automatically, which was the method of choice. However, the activity level of various samples differed widely, thus the attainment of ideal counting statistics would require manual operation in cases where fast counts would introduce time errors and where long counts would not be compatible with efficient use of the equipment. As a compromise between these extremes, the Nuclear-Chicago instrument was operated so as to obtain minimum counting times of 30 minutes for background samples and minimum total counts of 4000 for faster samples. In the latter case, no counting time of less than 5 minutes was recorded.

The Baird-Atomic system provided greater flexibility of operation in that it allowed background samples to be counted for total counts of

900 while the faster samples were counted for 9000 counts. This was accomplished by an auxiliary circuit which stopped the count at 900 if the activity of the sample was less than 150 counts per minute. Here again, the minimum counting time for background samples was 30 minutes while the faster samples were counted for at least 5 minutes.

Counting statistics applicable to the above counting conditions can be found in Appendix C.

Chemical and Biochemical Sampling

In order to evaluate the major parameters of treatment plant performance and to illustrate that the plant employed in this investigation was indeed operating under normal field conditions and attaining typical treatment efficiencies, the two major units -- the primary sedimentation basin and the trickling filter -- were subjected to a chemical and biochemical sampling program at the end of each run.

The sampling program applied to the primary settling tank was carried out by taking 1-hour composite samples from the influent and effluent of the basin. These samples, which were 1 gallon in volume, were analyzed for BOD and suspended solids.

The trickling filter was evaluated by obtaining samples from the influent, all ports and the effluent. The samples were composited over at least three dosing cycles and were 1 gallon in volume. In keeping with the concept that secondary sedimentation is an integral part of the trickling filter process, all preliminary samples were allowed 1 hour quiescent sedimentation before the final samples were taken. These samples were then analyzed for BOD, nitrates, and total nitrogen.

All chemical and biochemical analyses were conducted in accordance with the procedures outlined in Standard Methods for the Examination of Water and Wastewater (53).

CHAPTER VI

DISCUSSION OF OBSERVATIONS

General Considerations

In this study, relative counting techniques were utilized and a comparative analysis of the data was employed. Consequently, it was not necessary to correct the observed counts to absolute units of radioactivity. Since all radioactive samples from the same experiment were counted under virtually identical conditions in the same instrument, the relation between the observed activity and the true disintegrations was essentially constant. Application of an appropriate correction factor would have changed the absolute values of these data but would not have altered the relative magnitude of the established relationships.

The chemical forms and influent concentrations of the radioisotopes used in each experiment are tabulated in Table 2. In preparing these materials for dosing, the pH of each solution was adjusted so as to maintain the solubility of the radionuclides. Upon dosing, however, this solution was diluted into sewage having an average pH of 7.8. The characteristics of these materials in dilute solutions having slightly basic pH values indicate that all radioisotopes used, except cerium, iron, and cobalt which are known colloid formers, remained in their ionic form.

All experimental studies conducted during this investigation were undertaken at levels of activity that could be reasonably expected under

actual field conditions. Even though relatively high counting rates were often produced, the concentrations of radioactive materials were still very low. This is illustrated in Appendix B which gives the influent concentrations (in mg/l) of the radionuclides used in each experiment. Examination of these values indicates that the addition of radioactive materials in the concentrations used did not appreciably alter the nature or amount of soluble or insoluble solids present in the waste.

Removal by Primary Sedimentation

Tabulated data from the series of studies concerning this unit are contained in Appendix D. Inspection of these data permits two conclusions to be drawn. The first is that after the effluent activity approached equilibrium conditions, very little removal of soluble or colloidal radionuclides was accomplished by this treatment process. The steady state removal values varied from near 0 to 15 per cent with most falling between 5 and 10 per cent. The highest values recorded were obtained in the potassium-42 experiment but it is believed that this apparent increase in treatment efficiency resulted from the physical decay of this short half-life isotope rather than from actual removal by the unit.

The second conclusion is that all removal patterns were quite similar and, within the ranges investigated, seemed to be independent of the amount as well as the chemical and physical properties of the radionuclides utilized. Due to these similarities, the removal patterns from all experiments were averaged and the results are presented graphically in Figure 6. While the particular shape of this curve is a function of the design and operation of the basin investigated, it is

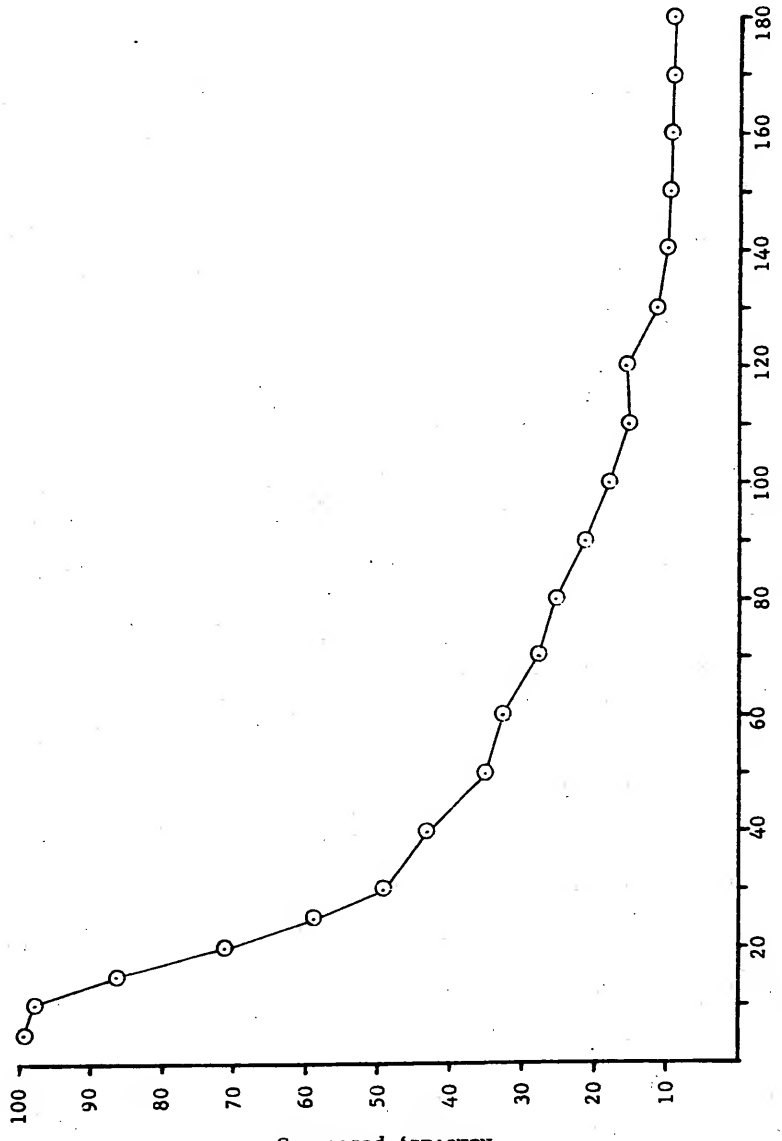

Fig. 6.- Average removal of selected radionuclides by primary sedimentation.

characteristic of the effluent patterns from this type of unit. In general, this figure indicates that after approximately 2 hours of continuous isotopic dosing, the effluent activity approached equilibrium conditions and that once these conditions were attained, the rate of removal stabilized at approximately 9 per cent.

The principal action occurring in treatment units of this general type is the physical removal of settleable solids by gravitational sedimentation. Since the nature of the radioactive materials used in this investigation did not permit them to be readily removed in this manner, the mechanism of removal appears to have been the sorption of the radionuclides by the settleable solids inherent in the waste. The operational characteristics of this treatment process and the nature and amount of settleable solids normally present in a waste of this type, indicate that the efficiency of this proposed mechanism would be low for colloidal and dissolved radioisotopes. This is substantiated by the observed data.

Removal by Trickling Filtration

Basic data and graphs concerning the experimental studies conducted on the trickling filtration and secondary sedimentation processes are contained in Appendix E. The various treatment efficiencies attained by these units operating under equilibrium conditions are summarized in Table 3. In studying Figures 16 through 23 and 26 through 29, it should be remembered that the observed activities (in c/m/mg) were dependent, to a large extent, on the influent concentration as well as the physical half-life of the radioactive material investigated.

TABLE 3

SUMMARY OF REMOVAL EFFICIENCIES ACHIEVED BY TRICKLING FILTRATION AND SECONDARY SEDIMENTATION UNDER EQUILIBRIUM CONDITIONS

Radionuclide	Average Percentage Removal by Various Depths of Filter Medium				Average Percentage Removal in Secondary Sedimentation Basin
	2'	4'	6'	8'	
K-42	15	35	45	49	27
Sr-89	24	27	37	42	23
I-131	26	42	53	61	3
P-32	32	36	43	46	0.4
MFP	40	48	61	63	40
Fe-59	46	58	72	65	70
Co-58	48	66	80	81	64
Ce-141, 144	57	63	78	81	48

Since these conditions varied from one experiment to another, these figures should be used only in making comparisons and observing general trends.

The trickling filter data represented graphically in Figures 8 through 15 permit several general observations to be made. One of the most significant of these is that all radioactive materials investigated experienced some degree of removal by this unit. Figures 16 through 23 not only substantiate the fact that this removal did occur but also indicate that the observed uptake resulted from the concentration of these materials by the zoogleal slimes present throughout the filter. Considering the presently accepted theory of trickling filter operation, the extent of the slime-liquid interface available for transfer within this unit and the relatively low concentration of radioactive materials used, it is understandable how such a removal could be obtained.

Another general trend recognizable in Figures 8 through 15 is that most removal patterns exhibited a high initial uptake followed by a somewhat asymptotic approach to equilibrium conditions. This is a fairly common characteristic of most chemical and biological systems and results from the gradual satisfaction of a comparatively high initial uptake capacity being superimposed on a steady rate of removal. A noted exception to this general behavior occurred during the phosphorus-32 experiment and was observed to coincide with a noticeable sloughing caused by a sharp, early morning rise in both the organic loading rate and the ambient temperature.

All filter uptake patterns indicate that the various rates of removal reached their equilibrium values approximately 12 hours (96 doses) after isotopic dosing started. This conclusion is supported by

the action occurring in the secondary sedimentation basin. Figures 24 through 29 show that, in general, the secondary sedimentation removal patterns and the activity of the secondary sludge, both of which depend on the action occurring in the filter, had attained their steady state conditions within 12 hours. These observations seem to indicate that the achievement of equilibrium conditions was a function more of the number of doses applied than of the physical and chemical characteristics of the radionuclides investigated.

The filter uptake patterns also indicate that the rate of removal with respect to depth generally decreased throughout the filter. This is illustrated in Table 3 which summarizes the various removal efficiencies observed after 24 hours of dosing. This table shows that in all experimental studies undertaken, the highest removals per increment of depth were obtained in the first 2 feet of medium and, in most experiments, this portion of the filter accomplished over half of the uptake attained by the entire unit. The middle 4 feet gave intermediate treatment while no appreciable removal was realized by the lower 2 feet of the filter bed. The activity of the filter slimes, shown graphically in Figures 16 through 23, express general agreement with this uptake pattern.

This somewhat exponential rate of removal is understandable since the uptake of soluble and colloidal radionuclides by this treatment process is dependent on the sorptive capacity of the zoogleal slimes present at the various depths in the filter and the concentration of radioactive materials available for removal at each level. Both of these factors were observed to decrease with increasing depth of filter medium.

A careful study of Table 3 indicates that by ranking the various materials investigated according to their corresponding degrees of removal, it is possible to distinguish two definite groups, separated by mixed fission products (MFP). The first group, which contains potassium-42, strontium-89, iodine-131 and phosphorus-32, experienced an uptake of approximately 50 per cent by an 8-foot filter. The second group, which contains iron-59, cobalt-58, and cerium-141, 144, experienced a comparable removal in the first 2 feet of medium and almost twice this value in the full 8-foot depth. Mixed fission products, which contain representative members of both groups, gave intermediate treatment. The treatment efficiencies obtained by the secondary sedimentation basin not only confirm this general division but also provide an indication of the nature and effectiveness of the action occurring in the filter.

Correlation of the various removal patterns and treatment efficiencies obtained in both the trickling filter and secondary sedimentation basin with the physical and chemical characteristics of the radioactive materials investigated, indicates that the mechanisms of uptake in the filter can be classified into three general categories. The first of these concerns the radionuclides that are significant in cell metabolism. In this case, the effective mechanism of removal appears to be the absorption of the radioactive materials by the microorganisms present in the zoogleal slime layer. The radionuclides in this category have to compete with their stable counterparts in the removal process; therefore, the uptake efficiency is dependent on the concentrations of stable isotopes present in the waste. Since sewage

normally contains comparatively high concentrations of the elements essential in cell metabolism, the isotopic dilution factor of this waste is relatively high. Consequently, the potential uptake capacity of metabolically significant radionuclides by the trickling filter process is somewhat low. This is illustrated by the phosphorus-32 uptake data summarized in Table 3. This table shows that in the presence of 5 to 7 milligrams per liter of stable orthophosphates, the experimental filter used in this investigation accomplished a relatively low uptake of 46 per cent.

The low removal of phosphorus-32 obtained in the secondary sedimentation basin indicates that as the filter slimes gradually sloughed off (due to continuous replacement procedures) and passed from the filter, the radiophosphorus which had undergone preliminary removal by the viable slimes in the unit was re-entrained in the waste stream and was no longer associated with settleable solids. This leads to the general observation that the over-all process of trickling filtration and secondary sedimentation was relatively ineffective in removing this radionuclide from sewage.

The second category of uptake mechanisms concerns the radioactive materials that are present in the waste in their soluble form but are not significant in cell metabolic processes. In this case the uptake mechanism appears to be that of ion exchange. The radionuclides subject to removal in this manner must not only compete with their stable counterparts but also with all other elements that have similar ionic properties or chemical behavior. This indicates that the isotopic and chemical dilution resulting from the wide range of stable materials

normally present in sewage, would limit the efficiency of this uptake mechanism. This is substantiated by the potassium-42, strontium-89, and iodine-131 data shown in Table 3. The relatively low removals indicated in this table are understandable since these materials had to compete with their chemically similar counterparts -- sodium, calcium, and chlorine -- present in the sewage. The low removal efficiencies obtained by secondary sedimentation indicate a re-entrainment similar to that explained above and lead to the same general conclusion concerning the ability of this treatment sequence to effectively remove these radionuclides from sewage.

The third general category of uptake mechanisms concerns the non-metabolically significant radionuclides that are present in the waste in their colloidal form. Here, the indicated modes of removal are adsorption and physical trapping of these materials on and in the zoogleal slime layer. According to the presently accepted theory of trickling filter operation, this uptake mechanism should be relatively effective in removing colloidal matter from the waste stream. This is supported by the iron-59, cobalt-58, and cerium-141, 144 data summarized in Table 3. As pointed out previously, these materials experienced a higher uptake than that indicated for the other radionuclides investigated. The comparatively high removal obtained by secondary sedimentation indicates that this uptake mechanism was effective in removing these colloidal radionuclides from the waste stream and associating them with the filter solids that eventually reached the secondary sedimentation basin in a settleable form.

Removal by Lagooning (Polishing Pond)

The tabulated data concerning this series of investigations are contained in Appendix F. Pertinent data derived from the influent and effluent activity patterns shown in Figures 30 through 36 are summarized in Table 4. In determining the various percentages of removal shown in this table, the total activity going into the basin over each 20-day study period was compared to the total activity leaving the basin during the same period. Since these activities were proportional to the areas under their respective influent and effluent curves, the indicated removal values were obtained by determining and comparing the appropriate areas.

TABLE 4

SUMMARY OF REMOVAL EFFICIENCIES AND BUFFERING FACTORS OBTAINED BY LAGOONING

Radionuclide	Removal Efficiency (Percentage)	Buffering Factor[a]
I-131	0	3.1
P-32	54	6.6
Co-58	55	3.3
MFP	58	7.0
Sr-89	69	9.7
Fe-59	86	13.
Ce-141, 144	93	15.

[a]Ratio of peak influent activity to peak effluent activity, averaged over all three dosing sequences.

Inspection of Table 4 and Figures 30 through 36 indicates that the relatively long detention time, the intimate algal-bacterial contact and the high dilution factor provided by this treatment process was effective in delaying, buffering and, in most cases, appreciably removing low-level "slugs" of the radionuclides investigated. The evident correlation of the buffering factors with the removal efficiencies points out that the ability of this unit to buffer "slugs" of radioactivity was not only dependent on the design and operation of the basin but also on the extent of the removal obtained within the unit. As indicated in the above table, the observed buffering factors varied from a minimum of 3.1 for I-131 to a maximum of 15 for Ce-141, 144. The lower value, which was obtained under the conditions of zero removal, indicates the dilution factor of the basin.

The various influent and effluent activities observed represent the total amount of radioactivity entering and leaving the basin regardless of chemical or physical form or biological association; therefore, the various removal efficiencies indicated in Table 4 represent the actual removal occurring within the unit. Since the half-lives of the indicated radionuclides were relatively long compared to the observed median detention time (2 days) of the basin, radioactive decay had no appreciable effect on these removal efficiencies. These considerations indicate that the observed removals resulted from the deposition of the radionuclides within the unit. In view of this, the indicated mechanisms of removal are precipitation by chemical, physical, and biological means and ion exchange reactions involving the radionuclides entrained in the waste stream and the stable materials retained in the basin.

The effectiveness of these mechanisms operating under the conditions of prolonged detention and intensive biological contact, is illustrated by the various removal efficiencies obtained. Except in the case of I-131, which exhibited a positive averaion to removal by these processes, all radionuclides investigated, especially colloidal cerium and iron, experienced significant removal.

Chemical and Biochemical Analyses

Investigational data concerning the chemical and biochemical parameters of treatment plant performance are tabulated in Appendix G. The trickling filter data summarized in Tables 54, 56, and 58 are presented graphically in Figure 7.

Inspection of Table 52 indicates that during the course of this investigation, the pilot plant influent contained, on the average, 135 milligrams per liter of suspended solids and had an average BOD equal to 170 milligrams per liter. The primary sedimentation data indicate that the unit used in this investigation accomplished an average BOD reduction of 28 per cent and an average reduction in suspended solids of 41 per cent. Both of these values fall within reasonable limits of operation for basins of this type.

Tables 53 through 58 show that the filter utilized in this study achieved average reductions in BOD and total nitrogen of 89 and 84 per cent, respectively, while effecting an average nitrification of 67 per cent. The various curves in Figure 7 indicate that the major portion of the observed treatment occurred within the first 5 feet of filter medium. These observations are within the ranges of normal operation

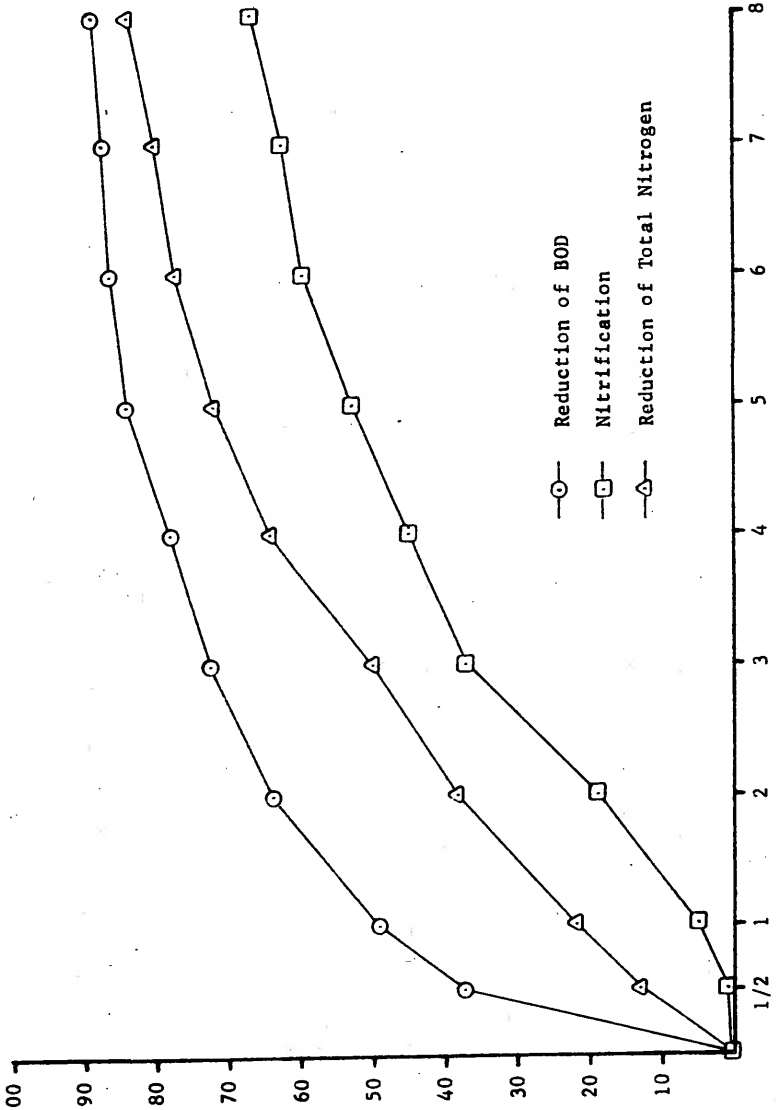

Fig. 7.- Relation of BOD, nitrates and total nitrogen with depth in filter.

and are in general agreement with the results of prior investigations conducted on this unit by Hagan (54), Vilaret (55), and Priede (56).

In general, the primary sedimentation basin and trickling filter employed in this investigation were observed to be operating under normal field conditions and attaining typical treatment efficiencies throughout the course of the experimental work. The presence of radioactive materials in the waste stream in the amounts used in this investigation had no apparent effects of these treatment processes.

CHAPTER VII

SUMMARY AND CONCLUSIONS

This investigation was concerned with evaluating the removal of low-level radionuclides from waste water by a complete sewage treatment plant operating under actual field conditions. In making this evaluation, a pilot size treatment plant employing primary sedimentation, trickling filtration, and lagooning was utilized. These treatment processes were subjected to a series of eight experiments involving phosphorus-32, iodine-131, potassium-42, cerium-141, 144, iron-59, cobalt-58, strontium-89, and mixed fission products.

Based on the results of the various radiological, chemical and biochemical determinations made during these experiments, the following conclusions have been drawn:

1. Primary sedimentation is relatively ineffective as a process for removing colloidal and dissolved radionuclides from sewage. After equilibrium of the effluent activity is established, removals of less than 10 per cent can be expected.
2. The effectiveness of the trickling filtration process in the treatment of low-level wastes is limited to its ability to remove the radioactive components from the main waste stream and to concentrate these materials in a relatively small volume of solid matter which, after passing from the filter, can be removed by sedimentation. Even though significant removal may occur within

the unit, the uptake mechanism may become reversible and the materials preliminarily removed in the filter may become re-entrained in essentially their original form. Consequently, the treatment efficiency of the over-all process of trickling filtration is reflected in the removal accomplished by secondary sedimentation. The approximate over-all removals that can be expected under the conditions of normal plant operation are: 60 to 70 per cent for iron-59 and cobalt-58; 40 to 50 per cent for cerium-141, 144 and mixed fission products; approximately 25 per cent for potassium-42 and strontium-89; and less than 5 per cent for iodine-131 and phosphorus-32.

3. The uptake of low-level radionuclides within a filter results from the concentration of these materials by the zoogleal slimes present throughout the unit. The rate of removal with respect to time is comparatively high during the initial doses but gradually decreases to equilibrium conditions. The attainment of stable uptake conditions is more a function of the number of doses applied than of the characteristics of the radioactive materials in the waste. Plants employing shorter dosing cycles than 7 minutes can expect to achieve equilibrium conditions in less than 12 hours (96 doses). The rate of removal with respect to depth decreases somewhat exponentially with increasing depth of medium. The optimum filter depth is 6 feet.

4. The concentration of radioactive materials by the zoogleal slimes in a trickling filter results from the action of three removal mechanisms, (a) absorption of the radionuclides by the microbiota

in the slime layer, (b) ion exchange reactions involving the radioisotopes in the waste stream and the stable elements associated with the filter solids, (c) adsorption and physical trapping of the radioactive materials on and in the zoogleal slime layer. The effectiveness of these uptake mechanisms is a function of the chemical and physical properties of the radionuclides and the concentration of their stable counterparts and chemically similar materials in the waste. As a result of the isotopic and chemical dilution provided by sewage, the mechanisms of absorption and ion exchange are relatively ineffective and highly reversible; consequently soluble radionuclides are not effectively removed. Colloidal radionuclides, being more amenable to removal by these mechanisms especially by adsorption and physical trapping, are efficiently and effectively removed.

5. The comparatively long detention time and intimate algal-bacterial contact provided by lagoons are effective in diluting, delaying and, in most cases, substantially removing "slugs" of low-level radioactive materials. Basins employing effective detention times of 2 to 3 days can expect to attain the following removals: 90 per cent for cerium-141, 144 and iron-59; 70 per cent for strontium-89; 50 to 60 per cent for phosphorus-32, cobalt-58 and mixed fission products; and less than 1 per cent for iodine-131.
6. The mechanisms effective in the removal of radioactive materials by lagooning are, (a) precipitation by chemical, physical, and biological means, (b) ion exchange reactions involving the

suspended radionuclides and the stable materials retained in the basin. These mechanisms are most effective in removing trivalent materials in their colloidal form and divalent elements biologically significant in trace amounts.

7. Sewage treatment plants operating under normal field conditions are able to receive and dispose of low-level radioactive wastes with no apparent decrease in treatment efficiency or changes in operational procedure required.

APPENDICES

APPENDIX A

CHEMICAL ANALYSIS OF LIMESTONE FILTER MEDIUM

Constituent	Percentage by Weight[a]
H_2O (103° C)	0.14 ± 0.03
CO_2 (600° C)	1.52 ± 0.14
$PO_4^{\equiv}$	trace (<0.01)
Mg^{++}	0.35 ± 0.04
Combined Oxides	3.14 ± 0.12
Ca^{++}	42.62 ± 0.41
Silica	8.48 ± 0.22
$CO_3^{=}$	36.42 ± 0.14
$SO_4^{=}$	1.88 ± 0.10
Fe^{++}	1.78 ± 0.04

[a]Average results of three stones picked at random.

APPENDIX B

CALCULATION OF CONCENTRATION OF RADIOACTIVE MATERIAL PRESENT AT SELECTED LEVELS OF RADIOACTIVITY

The concentrations of radioactive materials present in low-level wastes are usually very small. When the level of activity in picocuries per milliliter is known for a particular radioisotope, its concentration per milliliter may be calculated using the following relationship:

$$N = \frac{2.2 \times A}{\lambda}$$

where N is the number of unstable atoms present per milliliter, A is the level of activity in picocuries per milliliter and λ is the disintegration constant obtained by dividing 0.693 by the appropriate half-life T, expressed in minutes.

To express this concentration in terms of milligrams per liter, N must be multiplied by the proper atomic weight in grams, divided by Avogadro's number then multiplied by 10^6. Arrangement of these calculations into a single equation yields:

$$\text{Conc. (mg/l)} = \frac{A(\text{pc/ml}) \times 2.2 \times T(\text{min}) \times MW(\text{gms}) \times 10^6}{0.693 \times 6.023 \times 10^{23}(\text{atoms/mole})}$$

Indicated calculations for the activity levels used in this investigation have been made and the results are tabulated below.

Radionuclide	Activity (pc/ml)	Concentration (mg/l)
P-32	10 - 80	3.5×10^{-11} - 2.8×10^{-9}
I-131	20	1.6×10^{-10}
K-42	10 - 200	1.7×10^{-12} - 3.3×10^{-11}
Ce-141, 144	100	2.8×10^{-8}
Fe-59	30	6.0×10^{-10}
Co-58	45	1.4×10^{-9}
Sr-89	100	3.6×10^{-9}
MFP	50	- -

APPENDIX C

STATISTICS OF COUNTING RADIOACTIVE SAMPLES

Data obtained from most counting processes are known to follow a Poisson distribution, an outstanding property of which is that its standard deviation, σ, is the square root of its mean, μ. Unfortunately, in most experimental work, the true population mean is an unknown quantity. In such cases, the best estimate of μ can be obtained by making a number of observations, N, and calculating their mean $\bar{N}$. The best estimate of σ, symbolized by $\sigma(\bar{N})$, can then be obtained by taking the square root of $\bar{N}$.

However, in counting radioactive samples, it is not the standard deviation of the total count that is of concern but rather the standard deviation of the count rate, R', where

$$R' = \frac{N}{t}$$

In this expression, N represents the observed count recorded in time t. Since the accuracy of any count rate increases with increasing time of observation, the desired standard deviation must not only be a function of the observed count rate but also a function of the time over which this rate was determined. Applying the usual statistical methods for propagation of error to the Poisson distribution:

$$\sigma(R') = \left(\frac{N/t}{t}\right)^{\frac{1}{2}} = \left(\frac{R'}{t}\right)^{\frac{1}{2}} = \frac{(N)^{\frac{1}{2}}}{t}$$

In actual practice, all counting instruments have a background counting rate, B, which contributes to the gross counting rate, R_o. The sample counting rate, R, can be calculated as follows:

$$R = R_o - B$$

Applying the statistical methods for propagation of error yields:

$$\sigma(R) = \left(\frac{R_o}{t_1} - \frac{B}{t_2}\right)^{\frac{1}{2}}$$

where t_1 and t_2 are the times over which gross and background counting rates were determined.

Using gross counts of 4,000 and 9,000 observed over a minimum counting time of 5 minutes and a background of 15 counts per minute observed over a minimum time of 30 minutes, the following standard deviations and associated counting errors may be calculated.

$$\sigma(R) = \left(\frac{800}{5} - \frac{15}{30}\right)^{\frac{1}{2}} = 12.6 \text{ c/m} \qquad e = 1.96 \times 12.6 = 24.7 \text{ c/m}$$

$$\sigma(R) = \left(\frac{1800}{5} - \frac{15}{30}\right)^{\frac{1}{2}} = 19.0 \text{ c/m} \qquad e = 1.96 \times 19.0 = 37.2 \text{ c/m}$$

APPENDIX D

TABULATED DATA -- REMOVAL OF SELECTED RADIONUCLIDES BY PRIMARY SEDIMENTATION

TABLE 5

REMOVAL OF P-32 BY PRIMARY SEDIMENTATION

Time in Minutes	Run 1[a] Eff. c/m	Run 1[a] % Removal	Run 2[b] Eff. c/m	Run 2[b] % Removal	Run 3[c] Eff. c/m	Run 3[c] % Removal	Average % Removal
0	3.47	--	2.49	--	6.80	--	--
5	1.57	99.79	2.41	99.94	6.35	99.69	99.8
10	2.75	99.64	7.52	99.81	7.13	99.65	99.7
15	6.26	99.18	266.0	93.41	299.5	85.18	92.6
20	245.6	67.86	836.3	79.27	691.7	65.78	71.0
25	346.6	54.64	1621.	59.83	985.5	51.24	55.2
30	428.8	43.89	2027.	49.78	851.6	57.87	50.5
40	518.0	32.21	2280.	43.49	1483.	26.61	34.0
50	568.6	25.59	2445.	39.42	1394.	31.04	32.0
60	601.4	21.29	2579.	36.20	1124.	44.38	34.0
70	597.6	21.79	2706.	32.97	1606.	20.54	25.1
80	651.2	19.48	2847.	29.45	1628.	19.48	22.8
90	631.8	17.32	3177.	21.28	1560.	22.84	20.5
100	699.8	8.42	--	--	1633.	19.21	13.8
110	--	--	--	--	1782.	11.82	11.8
120	687.0	10.09	--	--	1750.	13.40	11.8
130	707.6	7.40	--	--	1857.	8.12	7.76
140	684.6	10.41	--	--	1893.	6.34	8.38
150	--	--	--	--	1864.	7.77	7.77
160	--	--	--	--	1809.	10.51	10.5
170	--	--	--	--	1857.	8.12	8.12
180	--	--	--	--	1816.	10.17	10.2

[a]Influent activity was 764.1 c/m.

[b]Influent activity was 4035 c/m.

[c]Influent activity was 2021 c/m.

TABLE 6

REMOVAL OF I-131 BY PRIMARY SEDIMENTATION

Time in Minutes	Run 1[a] Eff. c/m	Run 1[a] % Removal	Run 2[b] Eff. c/m	Run 2[b] % Removal	Run 3[c] Eff. c/m	Run 3[c] % Removal	Average % Removal
0	1.11	--	1.43	--	1.75	--	--
5	1.17	99.62	1.56	99.57	1.83	99.45	99.6
10	2.25	99.27	5.25	98.56	9.40	97.16	98.3
15	21.77	92.96	71.82	80.26	73.15	77.93	83.7
20	59.29	80.83	85.30	76.55	103.9	68.66	75.3
25	80.36	74.01	115.4	68.28	118.7	64.19	68.8
30	193.0	37.57	192.2	47.17	143.0	56.85	47.2
40	183.2	40.75	229.7	36.84	185.3	44.11	40.6
50	196.8	36.36	278.4	23.47	212.4	35.93	31.9
60	199.1	35.60	303.1	16.67	223.3	32.63	28.3
70	216.3	30.05	316.9	12.89	247.8	25.25	22.7
80	252.1	18.49	278.4	23.47	239.8	27.66	23.2
90	231.3	25.17	287.4	20.98	235.4	28.99	25.0
100	249.1	19.46	320.2	11.98	243.5	26.54	19.3
110	261.6	15.41	323.5	11.06	268.0	19.15	15.2
120	250.0	19.16	308.4	15.23	263.8	20.41	18.3
130	273.3	11.63	308.0	15.32	287.4	13.31	13.4
140	278.0	10.10	338.1	7.05	294.0	11.31	9.79
150	273.7	11.49	331.7	8.83	301.4	9.07	9.80
160	269.8	12.76	325.8	10.43	297.5	10.25	11.2
170	279.1	9.75	312.2	14.17	297.9	10.13	11.4
180	272.5	11.86	324.8	10.70	287.8	13.19	11.9

[a]Influent activity was 309.2 c/m.

[b]Influent activity was 363.8 c/m.

[c]Influent activity was 331.5 c/m.

TABLE 7

REMOVAL OF K-42 BY PRIMARY SEDIMENTATION

Time in Minutes	Run 1		Run 2[a]		Run 3[b]		Average
	Eff. c/m	% Removal	Eff. c/m	% Removal	Eff. c/m	% Removal	% Removal
0	--	--	0.69	--	0.00	--	--
5	--	--	0.77	97.40	0.00	100.0	98.7
10	--	--	1.52	94.87	0.00	100.0	97.4
15	--	--	3.23	89.10	7.92	87.85	88.5
20	--	--	8.21	72.29	15.49	76.24	74.3
25	--	--	--	--	23.11	64.55	64.6
30	--	--	13.55	54.27	23.94	63.28	58.5
40	--	--	14.73	50.29	25.09	61.51	55.9
50	--	--	17.97	39.35	36.06	44.68	42.0
60	--	--	18.73	36.79	33.89	48.01	42.4
70	--	--	19.27	34.96	41.36	36.55	35.8
80	--	--	17.32	41.55	45.73	29.85	35.7
90	--	--	20.18	31.89	49.02	24.80	28.4
100	--	--	21.22	28.38	47.30	27.44	27.9
110	--	--	19.88	32.91	48.61	25.43	29.2
120	--	--	21.12	28.72	48.15	26.14	27.4
130	--	--	25.24	14.82	52.90	18.85	16.8
140	--	--	23.75	19.84	57.93	11.14	15.5
150	--	--	26.08	11.98	55.09	15.49	13.7
160	--	--	25.63	13.50	59.02	9.47	11.5
170	--	--	25.96	12.39	59.87	8.16	10.3
180	--	--	25.58	13.67	57.81	11.32	12.5

[a]Influent activity was 29.63 c/m.

[b]Influent activity was 65.19 c/m.

TABLE 8

REMOVAL OF Ce-141, 144 BY PRIMARY SEDIMENTATION

Time in Minutes	Run 1[a] Eff. c/m	Run 1[a] % Removal	Run 2[b] Eff. c/m	Run 2[b] % Removal	Run 3[c] Eff. c/m	Run 3[c] % Removal	Average % Removal
0	5.94	--	1.87	--	6.94	--	--
5	3.95	99.90	2.08	99.96	4.07	99.92	99.9
10	32.79	99.15	3.63	99.93	8.72	99.82	99.6
15	797.4	79.26	413.7	91.68	163.7	96.69	89.2
20	1783.	53.63	1240.	75.06	1205.	75.63	68.1
25	2192.	42.98	1597.	67.89	2566.	48.09	53.0
30	2294.	40.33	2603.	47.66	2967.	39.97	42.6
40	2277.	40.79	3236.	34.94	2808.	43.19	39.6
50	2464.	35.91	3587.	27.88	2448.	30.23	31.3
60	2665.	30.68	3370.	32.24	3332.	32.58	31.8
70	2618.	31.89	3645.	26.71	3345.	32.32	30.3
80	3017.	21.53	3784.	23.91	3690.	25.33	23.6
90	2939.	23.56	4023.	19.12	3752.	24.08	22.2
100	2817.	26.74	4464.	10.24	3952.	20.05	19.0
110	3247.	15.54	4532.	8.88	3817.	22.78	15.7
120	3187.	17.12	4356.	12.42	3768.	23.76	17.8
130	3516.	8.55	4464.	10.24	4158.	15.87	11.6
140	3475.	9.62	4335.	12.85	4187.	15.29	12.6
150	3379.	12.11	4005.	19.48	4293.	13.14	14.9
160	3435.	10.66	4212.	15.31	4278.	13.44	13.1
170	3357.	12.68	4293.	13.69	4399.	11.01	12.5
180	3475.	9.62	4789.	4.52	4272.	13.56	9.23

[a]Influent activity was 3845 c/m.

[b]Influent activity was 4974 c/m.

[c]Influent activity was 4943 c/m.

TABLE 9

REMOVAL OF Fe-59 BY PRIMARY SEDIMENTATION

Time in Minutes	Run 1[a] Eff. c/m	Run 1[a] % Removal	Run 2[b] Eff. c/m	Run 2[b] % Removal	Run 3[c] Eff. c/m	Run 3[c] % Removal	Average % Removal
0	6.92	--	3.19	--	1.22	--	--
5	10.03	98.27	4.40	99.04	0.63	99.90	99.1
10	23.89	95.88	2.75	99.40	2.70	99.56	98.3
15	195.0	66.38	43.46	90.55	28.93	93.65	83.5
20	248.0	57.25	114.0	75.22	113.0	81.56	71.3
25	288.5	50.26	177.5	61.41	256.5	58.13	56.6
30	243.3	40.81	213.0	53.69	302.2	50.68	48.4
40	255.3	38.75	272.2	40.81	378.6	38.21	39.3
50	428.2	26.18	322.8	29.80	382.2	37.62	31.2
60	415.3	28.39	301.9	34.35	415.6	32.16	31.6
70	437.2	24.61	351.2	23.63	401.5	34.47	27.6
80	422.0	27.27	375.0	18.44	472.2	22.92	22.9
90	460.2	20.65	414.3	9.92	512.3	16.38	15.7
100	454.8	21.58	445.5	3.12	559.8	8.63	11.1
110	515.4	11.15	413.7	10.04	549.1	10.38	10.5
120	532.0	8.27	427.0	7.16	526.0	14.15	9.86
130	493.9	14.85	403.5	12.25	591.1	3.51	9.87
140	553.3	4.60	401.6	12.67	543.4	11.31	9.53
150	522.9	9.84	427.5	7.04	588.5	3.94	6.94
160	550.5	5.09	403.5	12.25	563.1	8.09	8.48
170	521.4	10.11	395.8	13.94	549.6	10.30	11.4
180	525.7	9.36	421.7	8.29	530.1	13.48	10.4

[a]Influent activity was 580.0 c/m.

[b]Influent activity was 459.9 c/m.

[c]Influent activity was 612.6 c/m.

TABLE 10

REMOVAL OF Co-58 BY PRIMARY SEDIMENTATION

Time in Minutes	Run 1[a] Eff. c/m	Run 1[a] % Removal	Run 2[b] Eff. c/m	Run 2[b] % Removal	Run 3[c] Eff. c/m	Run 3[c] % Removal	Average % Removal
0	2.65	--	2.44	--	1.36	--	--
5	2.61	99.15	1.75	99.33	2.58	99.26	99.2
10	2.82	99.08	5.18	98.01	1.59	99.54	98.9
15	38.24	87.51	29.67	88.61	8.00	97.71	91.3
20	88.43	71.13	77.22	70.37	73.21	79.00	73.5
25	125.3	59.10	105.5	59.52	132.4	62.01	60.2
30	138.5	54.76	145.9	44.01	173.8	50.16	49.6
40	133.8	56.31	148.9	42.87	165.5	52.52	50.6
50	154.9	49.42	172.2	33.93	186.9	46.40	43.2
60	179.9	41.26	188.9	27.49	208.6	40.17	36.3
70	181.7	40.68	196.6	24.56	240.0	31.16	32.1
80	206.9	32.44	221.7	14.94	244.7	29.81	25.7
90	220.5	28.01	232.1	10.92	266.2	23.65	20.9
100	256.0	16.40	231.9	11.02	287.2	17.63	15.0
110	267.6	12.61	243.0	6.77	296.3	15.01	11.5
120	261.4	14.64	223.7	14.17	296.3	15.01	14.6
130	271.4	11.39	232.8	11.66	315.9	9.39	10.8
140	276.0	9.87	231.6	11.13	302.6	13.21	11.4
150	264.9	13.50	241.7	7.25	300.1	13.91	11.6
160	289.9	5.33	250.4	3.90	326.2	6.44	5.22
170	290.8	5.06	255.6	1.91	327.9	5.95	4.31
180	277.6	9.34	241.6	7.28	321.2	7.87	8.16

[a] Influent activity was 306.2 c/m.

[b] Influent activity was 260.6 c/m.

[c] Influent activity was 348.6 c/m.

TABLE 11

REMOVAL OF Sr-89 BY PRIMARY SEDIMENTATION

Time in Minutes	Run 1		Run 2[a]		Run 3[b]		Average % Removal
	Eff. c/m	% Removal	Eff. c/m	% Removal	Eff. c/m	% Removal	
0	--	--	17.81	--	4.15	--	--
5	--	--	20.85	99.49	4.33	99.79	99.6
10	--	--	18.61	99.54	44.13	97.90	98.7
15	--	--	555.8	86.36	410.8	80.44	83.4
20	--	--	870.5	78.63	817.3	61.08	69.9
25	--	--	1279.	68.60	1176.	44.00	56.3
30	--	--	1649.	59.51	1311.	37.57	48.5
40	--	--	1876.	53.94	1385.	34.05	44.0
50	--	--	2317.	43.11	1423.	32.24	37.7
60	--	--	2648.	34.99	1480.	29.52	32.3
70	--	--	2655.	34.81	1652.	21.33	28.1
80	--	--	2713.	33.39	1619.	22.90	28.1
90	--	--	2889.	29.07	1740.	17.14	23.1
100	--	--	2889.	29.07	1815.	13.57	21.3
110	--	--	3026.	25.71	1837.	12.52	19.1
120	--	--	3200.	21.43	1888.	10.10	15.8
130	--	--	3501.	14.04	1921.	8.52	11.3
140	--	--	3950.	3.02	1837.	12.52	7.77
150	--	--	3674.	9.80	1968.	6.29	8.04
160	--	--	3734.	8.32	1860.	11.43	9.87
170	--	--	3886.	4.59	1892.	9.90	7.24
180	--	--	3833.	5.89	2000.	4.76	5.33

[a]Influent activity was 4073 c/m.

[b]Influent activity was 2100 c/m.

TABLE 12

REMOVAL OF MFP BY PRIMARY SEDIMENTATION

Time in Minutes	Run 1[a] Eff. c/m	Run 1[a] % Removal	Run 2[b] Eff. c/m	Run 2[b] % Removal	Run 3[c] Eff. c/m	Run 3[c] % Removal	Average % Removal
0	9.63	--	3.70	--	3.60	--	--
5	12.25	99.40	31.67	98.37	3.78	99.80	99.2
10	139.6	93.18	185.9	90.43	61.40	96.72	93.4
15	644.0	68.52	295.5	84.79	112.3	94.00	82.4
20	730.4	61.37	583.1	69.99	480.4	74.34	68.6
25	912.1	55.42	736.3	62.10	700.1	62.60	60.0
30	1004.	50.93	936.3	51.81	906.7	51.57	51.4
40	1310.	35.97	1051.	45.91	1060.	43.38	41.8
50	1344.	34.31	1377.	29.13	1143.	38.94	34.1
60	1681.	17.84	1333.	31.40	1198.	36.00	28.4
70	1768.	13.59	1388.	28.56	1301.	30.50	24.2
80	1734.	15.25	1375.	29.23	1450.	22.54	22.3
90	1727.	15.59	1499.	22.85	1598.	14.64	17.7
100	1668.	18.48	1578.	18.78	1488.	20.51	19.3
110	1724.	15.74	1897.	2.34	1637.	12.55	10.2
120	1675.	18.13	1778.	8.49	1619.	13.51	13.4
130	1700.	16.91	1699.	12.56	1694.	9.51	13.0
140	2040.	0.29	1647.	15.23	1833.	2.08	5.87
150	2022.	1.17	1778.	8.49	1687.	9.88	6.51
160	1938.	5.28	1764.	9.21	1747.	6.68	7.06
170	1885.	7.87	1807.	7.00	1760.	5.98	6.95
180	1834.	10.36	1796.	7.57	1830.	2.24	6.72

[a]Influent activity was 2046 c/m.

[b]Influent activity was 1943 c/m.

[c]Influent activity was 1872 c/m.

APPENDIX E

TABULATED DATA AND GRAPHS -- REMOVAL OF SELECTED RADIONUCLIDES BY TRICKLING FILTRATION AND SECONDARY SEDIMENTATION

TABLE 13

REMOVAL OF P-32 BY TRICKLING FILTRATION

Depth in Feet	Time in Hours	Run 1		Run 2		Run 3		Average
		Net c/m	% Removal	Net c/m	% Removal	Net c/m	% Removal	% Removal
0		5.46	--	38.76	--	0.92	--	--
2		5.56	--	42.80	--	19.46	--	--
4	0	5.08	--	32.96	--	24.09	--	--
6		3.65	--	32.08	--	31.31	--	--
8		4.91	--	32.86	--	21.04	--	--
0		249.0	--	2002.	--	2331.	--	--
2		216.8	12.93	1824.	8.91	2490.	0.00	7.28
4	2	183.3	26.39	1224.	38.85	1759.	24.54	29.9
6		148.4	40.38	1225.	38.81	1454.	37.60	38.9
8		115.7	53.52	1062.	46.97	1333.	42.81	47.8
0		213.6	--	3568.	--	2601.	--	--
2		195.5	8.47	3303.	7.42	3109.	0.00	5.30
4	4	191.0	10.62	3229.	9.49	2620.	0.00	6.70
6		145.2	32.03	2229.	37.52	1994.	23.35	31.0
8		116.6	45.42	2153.	39.65	2012.	22.63	35.9
0		232.5	--	--	--	3362.	--	--
2		193.5	16.70	--	--	3254.	3.20	9.95
4	8	190.8	17.92	--	--	2707.	19.46	18.7
6		147.6	36.51	--	--	2247.	33.17	34.8
8		119.1	48.79	--	--	2082.	38.07	43.4
0		415.7	--	2511.	--	3480.	--	--
2		279.6	32.73	1835.	26.92	2774.	20.29	26.6
4	12	240.9	42.06	1679.	33.13	2634.	24.31	33.2
6		233.0	43.94	1484.	40.91	2175.	37.49	40.8
8		220.2	47.03	1397.	44.39	2055.	40.94	44.1
0		452.0	--	2573.	--	3323.	--	--
2		270.1	40.09	1605.	37.61	2076.	19.49	32.4
4	24	277.6	38.55	1534.	40.40	2320.	30.20	36.4
6		237.2	47.53	1436.	44.20	2037.	38.70	43.5
8		209.5	53.66	1409.	45.24	2052.	38.26	45.7

TABLE 14

REMOVAL OF I-131 BY TRICKLING FILTRATION

Depth in Feet	Time in Hours	Run 1 Net c/m	Run 1 % Removal	Run 2 Net c/m	Run 2 % Removal	Run 3 Net c/m	Run 3 % Removal	Average % Removal
0		1.39	--	0.13	--	0.00	--	--
2		3.78	--	3.76	--	0.00	--	--
4	0	9.42	--	3.33	--	0.62	--	--
6		5.49	--	4.18	--	1.94	--	--
8		6.34	--	2.55	--	1.45	--	--
0		430.3	--	402.4	--	361.9	--	--
2		228.6	46.86	208.3	48.24	177.8	50.86	48.7
4	2	192.4	55.29	175.9	56.27	140.2	61.27	57.6
6		164.6	61.75	142.8	64.50	128.8	64.40	63.6
8		134.1	68.84	124.0	69.17	123.2	65.97	68.0
0		401.5	--	378.3	--	357.9	--	--
2		218.1	45.69	206.4	45.43	216.4	39.54	43.6
4	4	187.9	53.19	175.1	53.70	174.2	51.32	52.7
6		148.9	62.91	147.2	61.10	149.7	58.18	60.7
8		134.1	66.59	132.5	64.97	129.3	63.87	65.1
0		497.3	--	329.2	--	426.0	--	--
2		325.0	34.65	221.6	32.69	285.1	33.09	33.5
4	8	243.4	51.01	163.0	50.49	218.0	48.83	50.1
6		206.0	58.57	139.0	57.77	190.2	55.34	57.2
8		187.2	62.36	121.8	63.02	165.0	61.26	62.2
0		409.6	--	349.6	--	354.9	--	--
2		287.5	29.81	247.8	29.13	252.4	28.88	29.3
4	12	214.4	47.67	195.2	44.19	208.2	41.33	44.4
6		176.2	56.98	172.6	50.63	161.4	54.53	54.0
8		153.7	62.48	156.0	55.39	132.9	62.56	60.1
0		435.7	--	343.2	--	427.0	--	--
2		321.5	26.21	262.1	23.63	305.4	28.49	26.1
4	24	258.8	40.60	200.8	41.50	238.3	44.20	42.1
6		203.4	53.32	172.1	49.85	183.7	56.97	53.4
8		173.5	60.18	140.5	59.06	156.2	63.42	60.9

TABLE 15

REMOVAL OF K-42 BY TRICKLING FILTRATION

Depth in Feet	Time in Hours	Run 1 Net c/m	Run 1 % Removal	Run 2 Net c/m	Run 2 % Removal	Run 3 Net c/m	Run 3 % Removal	Average % Removal
0		0.11	--	0.00	--	0.00	--	--
2		0.79	--	0.00	--	0.00	--	--
4	0	1.02	--	0.00	--	0.09	--	--
6		0.53	--	0.00	--	0.00	--	--
8		0.53	--	0.00	--	0.00	--	--
0		452.6	--	19.21	--	13.17	--	--
2		321.0	29.07	12.11	36.96	9.24	29.84	32.0
4	2	275.5	39.12	11.15	41.96	8.30	36.98	39.4
6		231.0	48.97	8.84	53.98	6.42	51.25	51.4
8		194.6	57.01	8.88	53.77	6.60	49.89	53.6
0		582.8	--	23.08	--	15.11	--	--
2		477.8	18.02	17.37	24.74	11.85	21.58	21.4
4	4	367.1	37.01	14.35	37.82	9.53	36.93	37.2
6		349.4	40.04	12.05	47.79	8.32	44.94	44.3
8		257.0	55.90	11.80	48.87	7.29	51.71	52.2
0		317.4	--	27.56	--	13.91	--	--
2		279.3	12.02	23.65	14.19	11.11	20.13	15.4
4	8	212.5	33.06	18.70	32.15	9.75	29.91	31.7
6		187.2	41.03	15.14	45.07	7.66	44.93	43.7
8		158.6	50.03	12.69	53.96	7.10	48.96	51.2
0		--	--	13.08	--	16.30	--	--
2		--	--	11.25	13.99	13.38	17.91	16.0
4	12	--	--	9.14	30.12	11.10	31.90	31.0
6		--	--	7.87	39.83	9.12	44.05	42.0
8		--	--	5.88	55.04	8.81	45.95	50.5
0		--	--	15.62	--	9.64	--	--
2		--	--	13.72	12.16	7.88	18.26	15.2
4	24	--	--	10.30	34.06	6.19	35.79	34.9
6		--	--	8.27	47.06	5.58	42.12	44.6
8		--	--	7.21	53.84	5.40	43.98	48.9

TABLE 16

REMOVAL OF Ce-141, 144 BY TRICKLING FILTRATION

Depth in Feet	Time in Hours	Run 1 Net c/m	Run 1 % Removal	Run 2 Net c/m	Run 2 % Removal	Run 3 Net c/m	Run 3 % Removal	Average % Removal
0		2.19	--	10.14	--	34.56	--	--
2		3.30	--	17.81	--	42.59	--	--
4	0	0.87	--	20.94	--	37.04	--	--
6		3.00	--	23.31	--	27.15	--	--
8		1.73	--	26.21	--	34.67	--	--
0		2324.	--	3882.	--	3600.	--	--
2		931.7	59.92	1226.	68.43	1389.	61.41	63.2
4	2	580.3	75.03	1205.	68.95	1057.	70.65	71.5
6		429.4	81.53	723.5	81.36	622.4	81.60	81.5
8		221.8	90.46	414.4	89.32	316.6	91.21	90.3
0		3359.	--	3047.	--	3950.	--	--
2		1263.	62.39	965.2	68.32	1480.	62.53	64.4
4	4	857.9	74.46	729.6	76.05	970.9	75.42	75.3
6		624.3	81.41	532.6	82.52	644.0	83.70	82.5
8		467.4	86.09	487.8	83.99	345.9	91.24	87.1
0		3361.	--	4375.	--	3118.	--	--
2		1500.	55.37	1539.	64.83	1185.	61.99	60.7
4	8	907.1	73.01	1143.	73.88	862.4	72.34	73.1
6		670.1	80.07	786.7	82.02	491.4	84.24	82.1
8		530.4	84.22	612.5	86.00	359.2	88.48	86.2
0		2997.	--	4486.	--	4021.	--	--
2		1342.	55.21	1713.	61.81	1488.	63.00	60.0
4	12	798.9	73.34	1170.	73.91	974.2	75.77	74.3
6		644.1	78.51	807.0	82.01	730.2	81.84	80.8
8		544.3	81.84	673.4	84.99	520.6	87.05	84.6
0		2721.	--	3143.	--	3065.	--	--
2		1495.	45.04	1098.	65.07	1224.	60.07	56.7
4	24	802.8	70.49	1058.	66.33	1066.	65.23	63.4
6		631.0	76.81	712.6	77.33	636.8	79.23	77.8
8		630.5	76.83	620.6	80.26	422.9	86.20	81.1

TABLE 17

REMOVAL OF Fe-59 BY TRICKLING FILTRATION

Depth in Feet	Time in Hours	Run 1 Net c/m	Run 1 % Removal	Run 2 Net c/m	Run 2 % Removal	Run 3 Net c/m	Run 3 % Removal	Average % Removal
0		2.40	--	3.81	--	5.47	--	--
2		4.99	--	6.04	--	5.21	--	--
4	0	6.81	--	6.63	--	6.10	--	--
6		5.93	--	7.17	--	6.47	--	--
8		10.94	--	19.33	--	18.44	--	--
0		287.1	--	237.3	--	282.7	--	--
2		127.6	55.57	105.2	55.68	136.1	51.88	54.4
4	2	77.18	73.11	69.93	70.54	89.51	68.34	70.7
6		43.67	84.79	37.18	84.35	42.41	85.00	84.7
8		41.70	85.47	50.28	78.82	50.04	82.30	82.2
0		364.8	--	312.2	--	264.4	--	--
2		173.3	52.48	147.5	52.75	131.9	50.11	51.8
4	4	119.9	67.12	96.38	69.13	92.48	65.03	67.1
6		65.26	82.11	59.53	80.93	64.20	75.72	79.6
8		57.84	84.14	66.15	78.81	65.65	75.17	79.4
0		344.1	--	340.1	--	287.6	--	--
2		174.8	49.18	178.4	47.54	149.8	47.91	48.2
4	8	150.9	56.16	124.0	63.55	111.6	61.21	60.3
6		92.72	73.06	86.03	74.71	79.02	72.53	73.4
8		92.09	73.24	69.16	79.67	71.65	75.09	76.0
0		227.6	--	220.2	--	198.3	--	--
2		134.7	40.81	127.6	42.04	99.49	49.82	44.2
4	12	109.4	51.94	94.83	56.93	73.69	62.84	57.2
6		58.96	74.09	67.03	69.56	48.72	75.43	73.0
8		60.74	73.31	62.35	71.68	55.59	71.96	72.3
0		213.1	--	227.3	--	191.8	--	--
2		119.6	43.85	136.0	40.15	88.61	53.79	45.9
4	24	94.31	55.74	95.49	57.99	77.34	59.67	57.8
6		50.20	76.44	60.00	73.60	65.66	65.76	71.9
8		71.50	66.45	83.62	63.21	66.36	65.40	65.0

TABLE 18

REMOVAL OF Co-58 BY TRICKLING FILTRATION

Depth in Feet	Time in Hours	Run 1 Net c/m	Run 1 % Removal	Run 2 Net c/m	Run 2 % Removal	Run 3 Net c/m	Run 3 % Removal	Average % Removal
0		1.73	--	3.72	--	2.93	--	--
2		6.45	--	6.66	--	6.33	--	--
4	0	5.59	--	4.97	--	6.55	--	--
6		5.35	--	4.92	--	5.88	--	--
8		5.24	--	8.08	--	6.77	--	--
0		161.2	--	165.6	--	162.3	--	--
2		72.62	54.95	74.69	54.89	71.07	56.22	55.4
4	2	54.69	66.07	55.02	66.77	43.90	72.96	68.6
6		24.92	84.54	27.35	83.48	25.03	84.58	84.2
8		22.97	85.75	25.57	84.56	20.71	87.24	85.9
0		184.1	--	173.6	--	194.2	--	--
2		88.50	51.94	82.16	52.67	97.01	50.06	51.6
4	4	68.82	62.63	54.16	68.80	57.76	70.26	67.2
6		34.16	81.45	36.49	78.98	35.59	81.68	80.7
8		34.30	81.37	28.05	83.84	29.36	84.88	83.4
0		179.2	--	178.3	--	196.1	--	--
2		80.85	54.90	82.23	53.88	99.54	49.25	52.7
4	8	58.52	67.35	53.58	69.95	80.50	58.96	65.4
6		40.66	77.32	38.14	78.61	43.45	77.85	77.9
8		33.80	81.14	31.99	82.06	42.58	78.29	80.5
0		167.2	--	--	--	200.0	--	--
2		97.34	41.78	--	--	111.0	44.50	43.1
4	12	59.61	64.35	--	--	67.04	66.48	65.4
6		38.44	77.01	--	--	40.77	79.61	78.3
8		33.82	79.77	--	--	33.39	83.30	81.5
0		132.7	--	177.7	--	144.2	--	--
2		84.75	36.13	80.49	54.70	69.44	51.84	47.6
4	24	51.14	61.46	55.32	68.86	45.58	68.39	66.2
6		29.17	78.02	27.01	84.80	30.90	78.57	80.5
8		30.64	76.91	31.13	82.48	23.83	83.07	81.0

TABLE 19

REMOVAL OF Sr-89 BY TRICKLING FILTRATION

Depth in Feet	Time in Hours	Run 1 Net c/m	Run 1 % Removal	Run 2 Net c/m	Run 2 % Removal	Run 3 Net c/m	Run 3 % Removal	Average % Removal
0		2.69	--	5.26	--	5.40	--	--
2		9.32	--	63.08	--	84.10	--	--
4	0	5.82	--	48.58	--	63.93	--	--
6		4.43	--	52.48	--	62.53	--	--
8		3.80	--	31.48	--	48.11	--	--
0		1686.	--	1814.	--	1554.	--	--
2		628.0	62.75	1055.	41.84	791.9	49.04	51.2
4	2	465.1	72.41	688.8	62.03	623.2	59.90	64.8
6		216.4	87.16	297.2	83.62	323.7	79.17	83.3
8		120.0	92.88	222.9	87.71	226.6	85.42	88.7
0		1376.	--	2444.	--	1918.	--	--
2		802.5	41.68	1440.	41.08	1082.	43.59	42.1
4	4	584.7	57.51	908.6	62.82	809.6	57.79	59.4
6		356.2	74.11	585.5	76.04	437.8	77.18	75.8
8		232.3	83.12	484.7	80.17	366.5	80.89	81.4
0		1550.	--	2102.	--	1633.	--	--
2		929.5	40.03	1221.	41.91	1254.	23.21	35.0
4	8	802.5	48.23	1117.	46.86	1053.	35.52	43.5
6		566.5	64.03	702.8	66.57	670.1	58.97	63.2
8		472.4	69.52	579.0	72.45	655.4	59.87	67.3
0		1490.	--	2225.	--	1842.	--	--
2		1040.	30.20	1552.	30.25	1441.	21.77	27.4
4	12	764.1	48.72	1338.	39.87	1095.	40.55	43.0
6		691.9	53.56	1034.	53.53	981.8	46.70	51.3
8		661.6	55.60	1072.	51.82	812.7	55.88	54.4
0		1540.	--	2196.	--	1714.	--	--
2		1143.	25.78	1609.	26.73	1397.	18.50	23.7
4	24	1060.	31.17	1589.	27.64	1329.	22.46	27.1
6		919.3	40.31	1243.	43.40	1229.	28.30	37.3
8		847.5	44.97	1183.	46.13	1095.	36.12	42.4

TABLE 20

REMOVAL OF MFP BY TRICKLING FILTRATION

Depth in Feet	Time in Hours	Run 1 Net c/m	Run 1 % Removal	Run 2 Net c/m	Run 2 % Removal	Run 3 Net c/m	Run 3 % Removal	Average % Removal
0		2.40	--	7.65	--	6.60	--	--
2		32.25	--	68.44	--	40.31	--	--
4	0	30.75	--	46.80	--	45.55	--	--
6		29.57	--	41.39	--	39.13	--	--
8		12.78	--	32.37	--	30.57	--	--
0		1764.	--	1269.	--	1085.	--	--
2		879.3	50.15	699.2	44.90	596.5	45.02	46.7
4	2	604.1	65.75	395.3	68.85	346.2	68.09	67.6
6		336.3	80.94	250.1	80.29	208.5	80.78	80.7
8		253.5	85.63	199.5	84.60	173.4	84.02	84.7
0		1631.	--	1262.	--	1101.	--	--
2		784.1	51.93	759.6	39.81	607.5	44.82	45.5
4	4	--	--	430.6	65.88	445.0	59.58	62.7
6		359.3	77.97	312.4	75.25	281.3	74.45	75.9
8		322.1	80.25	243.2	80.73	231.7	78.96	80.0
0		1754.	--	1023.	--	1033.	--	--
2		915.0	47.83	766.4	25.08	619.9	39.99	37.6
4	8	765.3	56.37	525.9	48.59	513.6	50.28	51.7
6		458.9	73.84	354.6	65.34	351.4	65.98	68.4
8		481.9	73.53	306.9	70.00	258.0	75.02	72.8
0		1730.	--	1064.	--	1024.	--	--
2		994.5	42.51	662.0	37.78	634.0	38.09	39.5
4	12	764.7	55.80	540.4	49.21	517.2	49.49	51.5
6		471.0	72.77	364.5	65.74	338.6	66.93	68.5
8		485.8	71.92	323.4	69.61	312.1	69.52	70.3
0		1755.	--	1127.	--	1089.	--	--
2		937.8	46.56	751.0	33.36	654.1	39.94	40.0
4	24	829.0	52.76	629.4	44.15	565.5	48.07	48.3
6		566.2	67.74	500.1	55.63	436.0	59.96	61.0
8		511.6	68.57	453.7	59.74	414.1	61.97	63.4

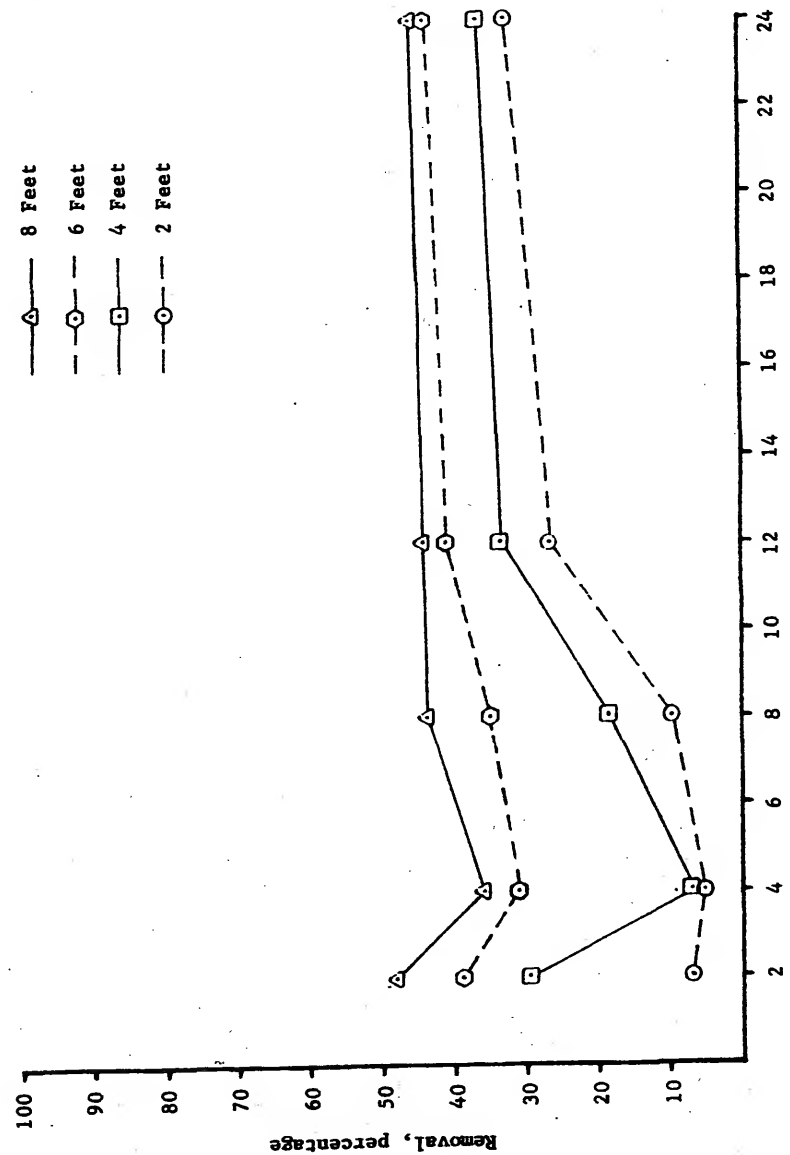

Fig. 8.- Removal of P-32 by trickling filtration.

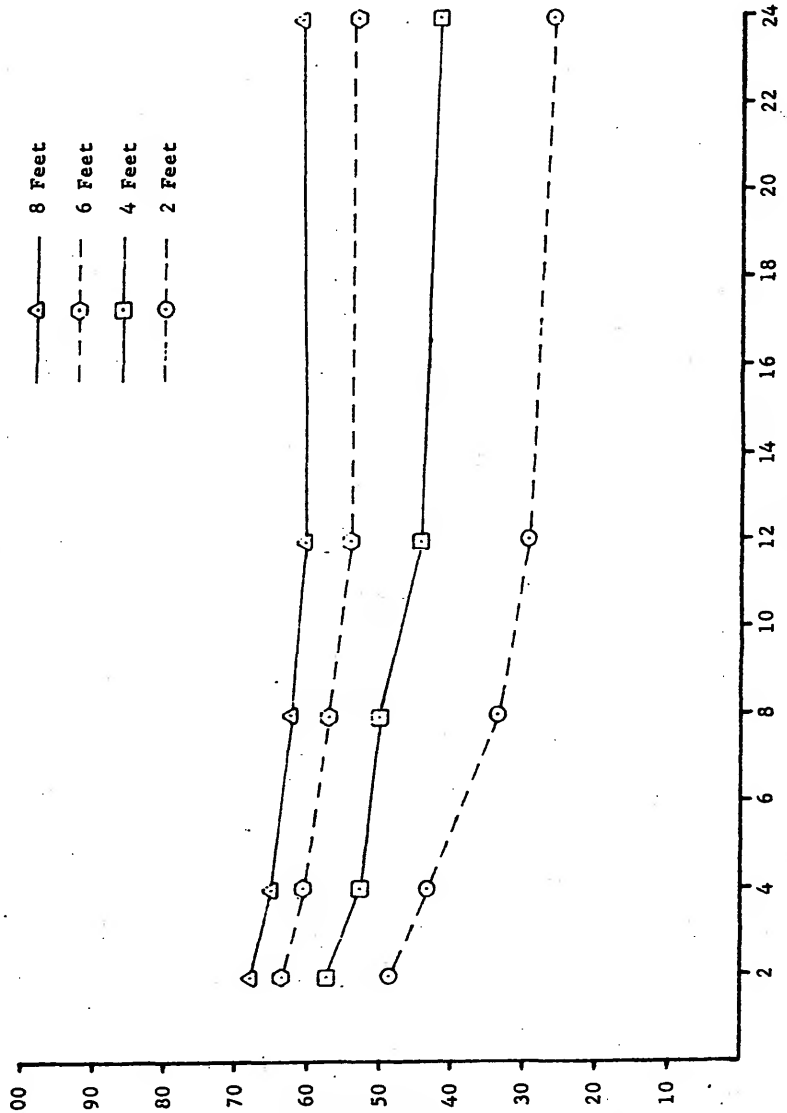

Fig. 9.- Removal of I-131 by trickling filtration.

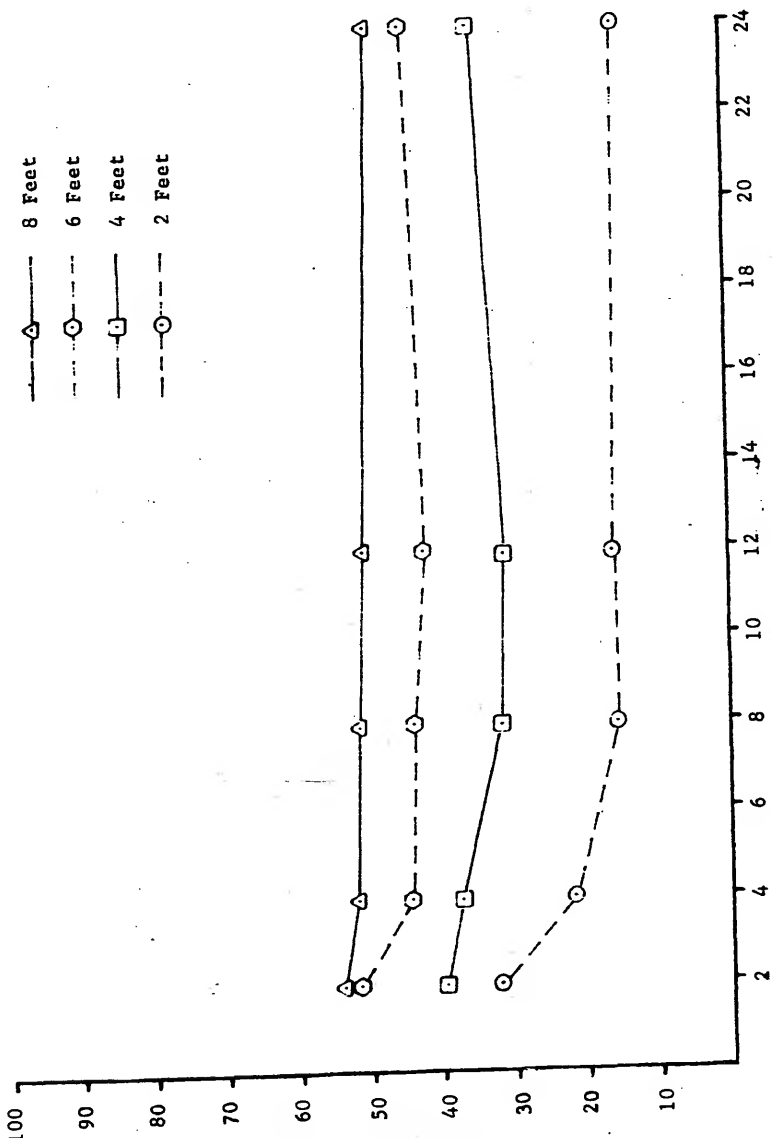

Fig. 10.- Removal of K-42 by trickling filtration.

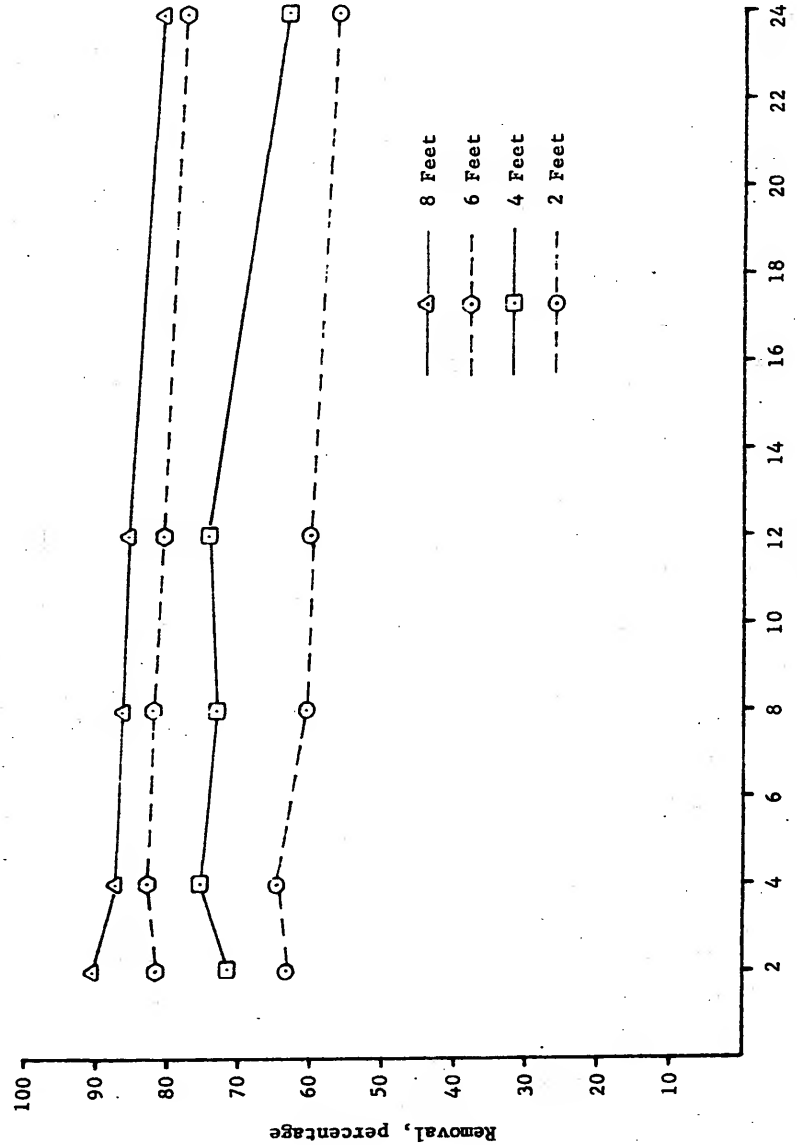

Fig. 11.- Removal of Ce-141, 144 by trickling filtration.

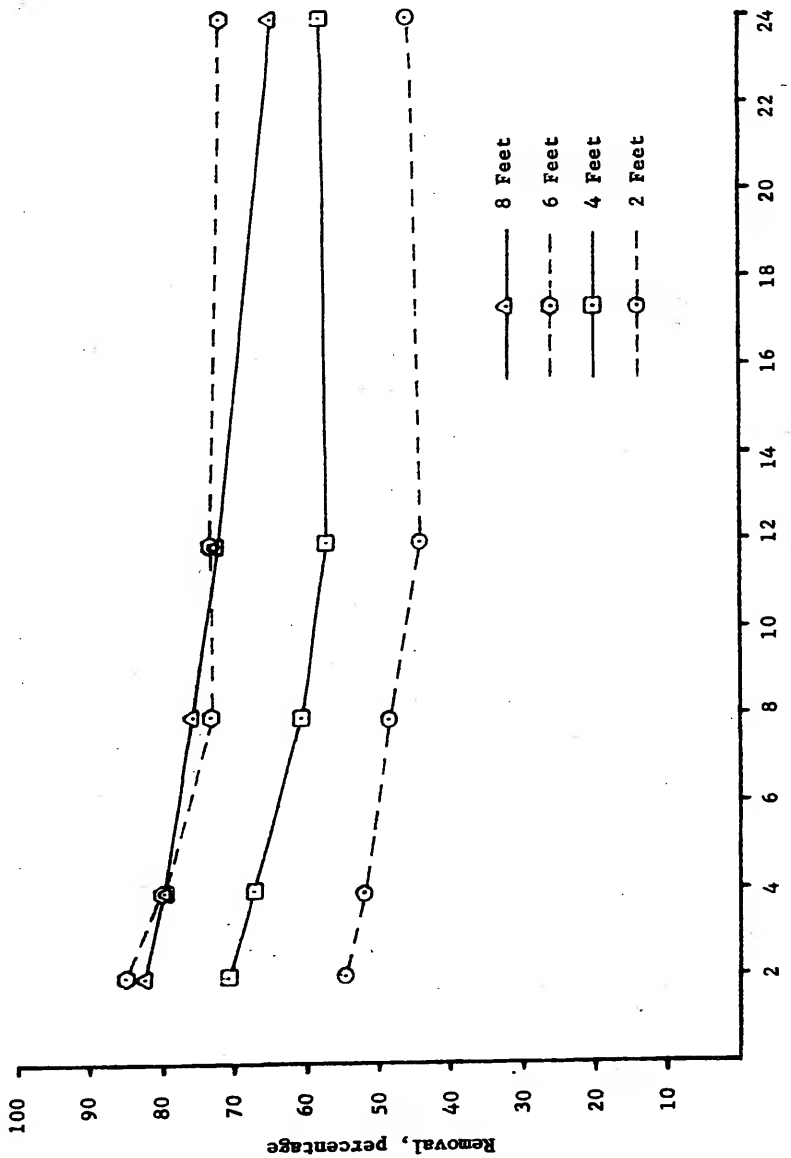

Fig. 12.- Removal of Fe-59 by trickling filtration.

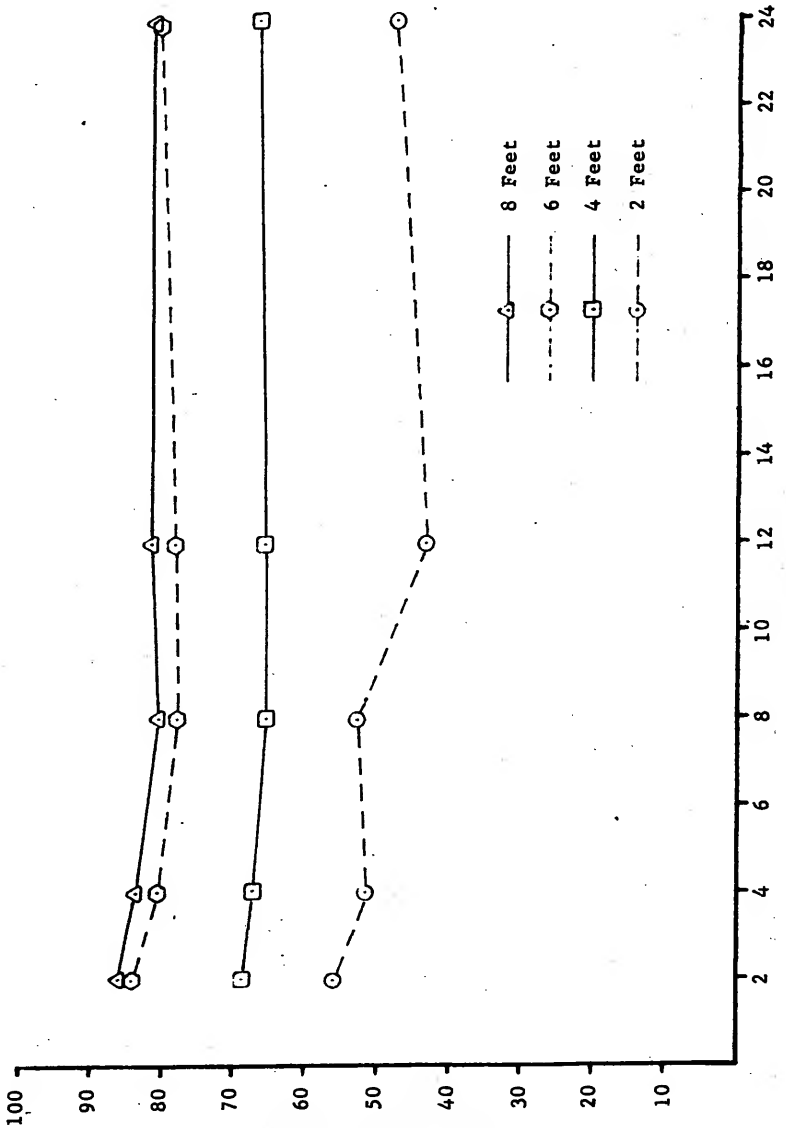

Fig. 13.- Removal of Co-58 by trickling filtration.

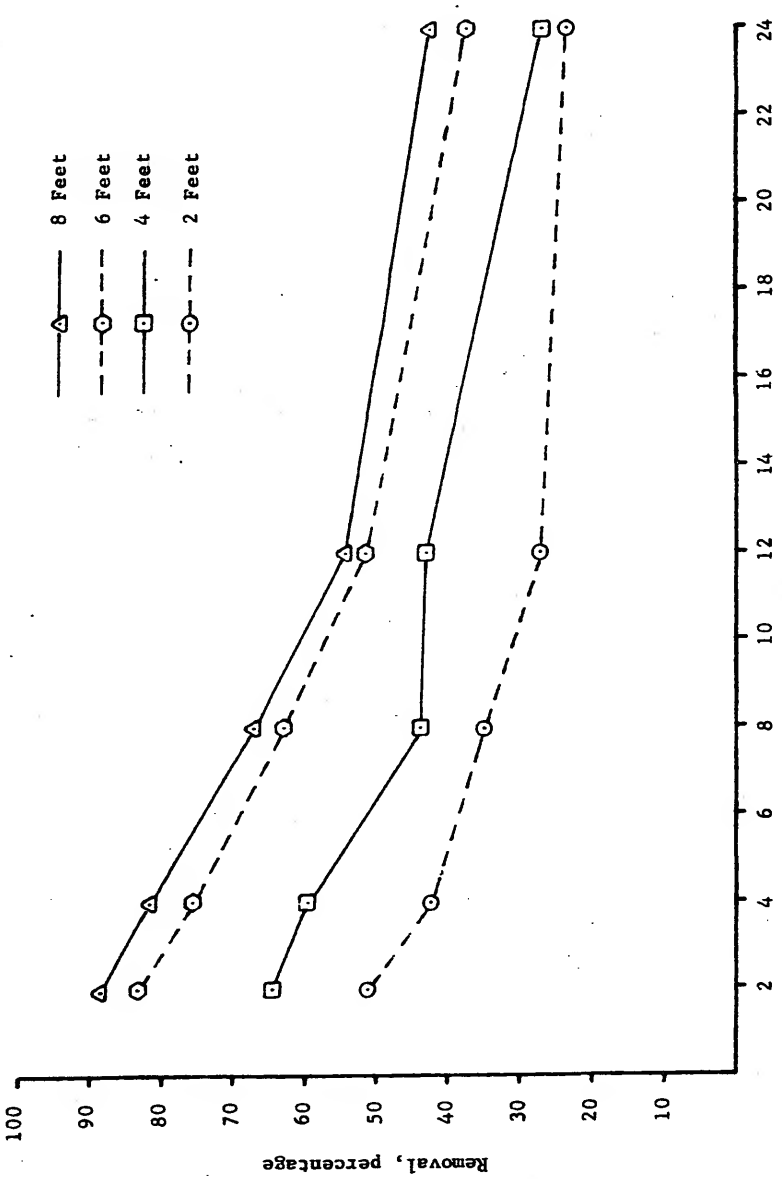

Fig. 14.- Removal of Sr-89 by trickling filtration.

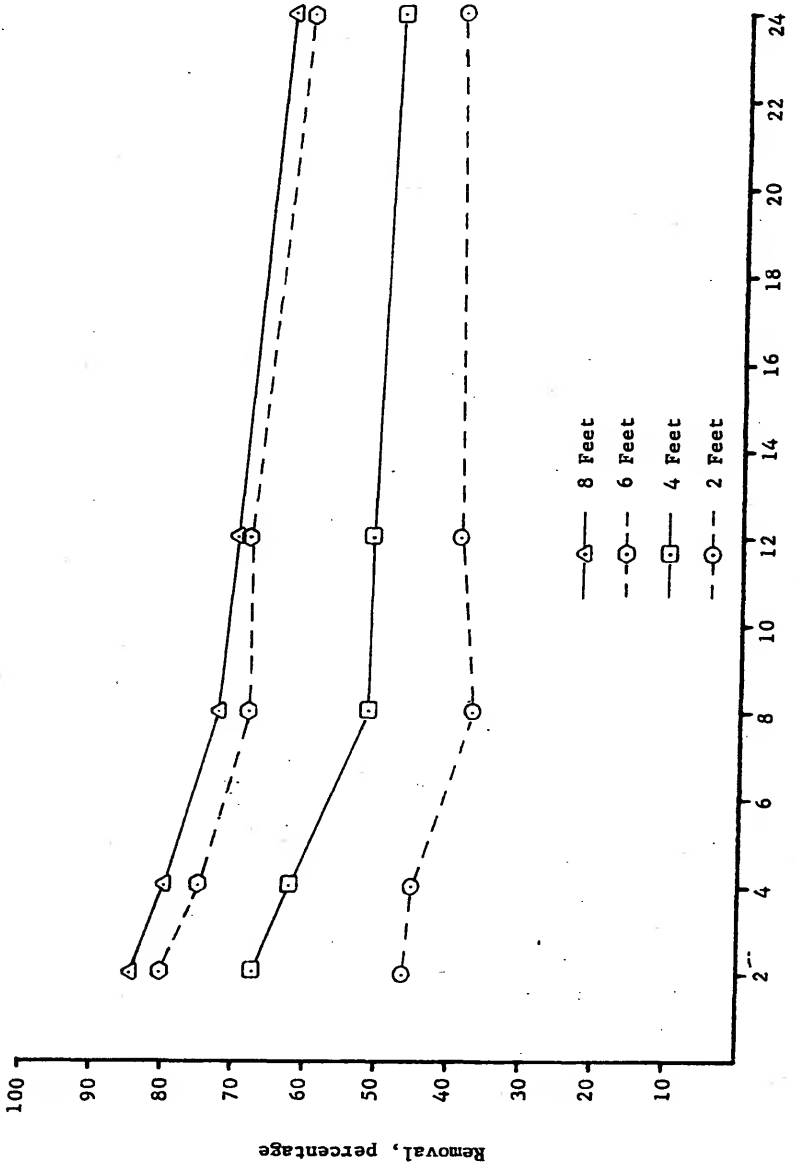

Fig. 15.- Removal of MFP by trickling filtration.

TABLE 21

ACTIVITY OF P-32 IN FILTER SLIMES

Depth in Feet	Activity (c/m/mg)							
	Run 1		Run 2		Run 3		Average	
	0 Hr.	24 Hr.	0 Hr.	24 Hr.	0 Hr.	24 Hr.	Runs 1 & 2 0 Hr.	Runs 2 & 3 24 Hr.
1/2	0.09	9.57	0.59	51.9	1.39	74.1	0.34	63.0
1	0.10	6.25	0.72	46.7	4.23	61.0	0.41	53.8
2	0.13	5.13	0.95	40.0	3.77	47.3	0.54	43.6
3	0.10	2.57	0.44	25.8	4.72	46.8	0.27	36.3
4	0.12	4.18	1.11	29.1	4.57	37.5	0.62	33.3
5	0.15	1.67	0.58	16.4	3.69	37.4	0.36	26.9
6	0.03	2.94	0.84	19.0	3.27	41.0	0.44	30.0
7	0.13	4.27	0.82	13.1	1.71	16.7	0.48	14.9

TABLE 22

ACTIVITY OF I-131 IN FILTER SLIMES

Depth in Feet	Activity (c/m/mg)							
	Run 1		Run 2		Run 3		Average	
	0 Hr.	24 Hr.	0 Hr.	24 Hr.	0 Hr.	24 Hr.	0 Hr.	24 Hr.
1/2	0.11	6.97	0.12	9.02	0.07	5.77	0.10	7.25
1	0.19	13.5	0.16	11.5	0.11	12.0	0.15	12.3
2	0.12	10.4	0.17	10.3	0.19	8.51	0.16	9.72
3	0.19	9.09	0.23	10.7	0.19	7.88	0.20	9.21
4	0.24	9.99	0.24	11.7	0.23	8.27	0.24	9.99
5	0.26	8.98	0.28	11.1	0.11	8.15	0.22	9.43
6	0.21	7.89	0.16	11.6	0.26	7.07	0.21	8.84
7	0.51	9.75	0.50	11.0	0.57	8.26	0.53	9.68

TABLE 23

ACTIVITY OF K-42 IN FILTER SLIMES

Depth in Feet	Activity (c/m/mg)							
	Run 1		Run 2		Run 3		Average Runs 2 & 3	
	0 Hr.	24 Hr.	0 Hr.	24 Hr.	0 Hr.	24 Hr.	0 Hr.	24 Hr.
1/2	0.36	28.4	0.18	2.73	0.15	1.50	0.23	1.94
1	0.43	27.2	0.25	2.99	0.11	1.37	0.26	2.18
2	0.41	26.3	0.13	2.56	0.24	1.20	0.26	1.88
3	0.35	22.6	0.37	2.19	0.02	1.01	0.25	1.60
4	0.53	17.4	0.20	1.69	0.05	0.85	0.26	1.27
5	0.50	16.9	0.34	1.48	0.07	0.94	0.30	1.21
6	0.38	16.0	0.33	1.30	0.17	0.87	0.29	1.08
7	0.34	13.9	0.31	1.59	0.10	0.58	0.25	1.08

TABLE 24

ACTIVITY OF Ce-141, 144 IN FILTER SLIMES

Depth in Feet	Activity (c/m/mg)							
	Run 1		Run 2		Run 3		Average Runs 2 & 3	
	0 Hr.	24 Hr.	0 Hr.	24 Hr.	0 Hr.	24 Hr.	0 Hr.	24 Hr.
1/2	0.15	712.	108.	722.	92.2	582.	100.	672.
1	0.13	502.	27.9	608.	58.3	538.	43.1	549.
2	0.15	427.	36.5	382.	54.9	476.	45.7	429.
3	0.05	399.	51.5	352.	24.6	377.	38.0	376.
4	0.03	388.	32.0	302.	49.5	353.	40.8	348.
5	0.03	190.	90.4	305.	53.2	262.	71.8	252.
6	0.81	195.	35.6	188.	53.5	211.	44.6	198.
7	0.05	112.	76.7	67.5	51.4	248.	64.0	143.

TABLE 25

ACTIVITY OF Fe-59 IN FILTER SLIMES

Depth in Feet	Activity (c/m/mg)							
	Run 1		Run 2		Run 3		Average	
	0 Hr.	24 Hr.	0 Hr.	24 Hr.	0 Hr.	24 Hr.	0 Hr.	24 Hr.
1/2	2.59	51.4	1.60	53.5	1.26	38.4	1.82	47.8
1	4.25	48.4	5.31	46.2	2.85	33.5	4.14	42.7
2	8.87	33.2	8.32	41.3	5.86	26.6	7.69	33.7
3	14.3	26.0	7.52	21.6	5.98	18.1	9.26	21.9
4	11.6	33.6	8.96	29.5	6.94	25.3	9.17	29.4
5	15.1	34.2	11.7	24.7	12.9	20.2	13.2	26.4
6	17.2	34.8	20.5	28.8	15.7	26.9	17.8	30.2
7	24.5	35.4	24.0	26.4	24.4	23.4	24.3	28.4

TABLE 26

ACTIVITY OF Co-58 IN FILTER SLIMES

Depth in Feet	Activity (c/m/mg)							
	Run 1		Run 2		Run 3		Average Runs 2 & 3	
	0 Hr.	24 Hr.	0 Hr.	24 Hr.	0 Hr.	24 Hr.	0 Hr.	24 Hr.
1/2	0.35	14.5	0.88	11.9	1.06	18.7	0.97	15.0
1	0.42	9.11	1.54	14.8	1.79	14.0	1.66	12.6
2	0.53	10.6	2.99	8.69	3.99	13.1	3.49	10.8
3	1.18	9.68	4.20	11.1	6.13	13.0	5.16	11.3
4	1.83	11.2	4.29	12.5	6.57	12.0	5.43	11.9
5	3.09	9.98	6.02	11.4	7.02	14.3	6.52	11.9
6	4.01	11.4	7.09	12.0	7.07	12.4	7.08	11.9
7	4.83	9.05	8.32	11.0	8.98	9.26	8.65	9.77

TABLE 27

ACTIVITY OF Sr-89 IN FILTER SLIMES

Depth in Feet	Activity (c/m/mg)							
	Run 1		Run 2		Run 3		Average	
	0 Hr.	24 Hr.	0 Hr.	24 Hr.	0 Hr.	24 Hr.	0 Hr.	24 Hr.
1/2	0.59	21.5	0.38	26.9	0.45	18.9	0.47	22.4
1	1.10	19.6	1.15	27.9	1.22	17.3	1.16	21.6
2	2.95	22.8	2.46	25.4	2.70	21.3	2.70	23.2
3	4.48	22.0	2.54	25.7	2.30	17.4	3.11	21.7
4	2.76	19.9	2.78	25.3	3.74	20.3	3.09	21.8
5	5.10	20.6	4.27	21.8	4.06	17.2	4.48	19.9
6	6.88	18.4	5.13	20.8	6.43	13.5	6.15	17.6
7	4.04	14.2	3.71	13.8	3.12	10.2	3.62	12.7

TABLE 28

ACTIVITY OF MFP IN FILTER SLIMES

Depth in Feet	Activity (c/m/mg)							
	Run 1		Run 2		Run 3		Average Runs 2 & 3	
	0 Hr.	24 Hr.	0 Hr.	24 Hr.	0 Hr.	24 Hr.	0 Hr.	24 Hr.
1/2	0.51	313.	6.77	250.	5.10	201.	5.93	255.
1	1.01	189.	11.7	127.	8.59	146.	10.1	154.
2	1.90	102.	10.8	89.2	9.99	91.7	10.4	94.3
3	2.25	91.7	8.12	99.1	7.42	87.6	7.77	92.8
4	2.76	95.3	8.34	106.	8.61	66.1	8.47	89.1
5	3.06	80.0	8.20	59.9	7.77	77.5	7.99	72.5
6	4.34	59.7	9.74	32.7	9.84	45.4	9.79	45.9
7	2.92	41.1	12.0	36.6	11.1	31.3	11.5	36.3

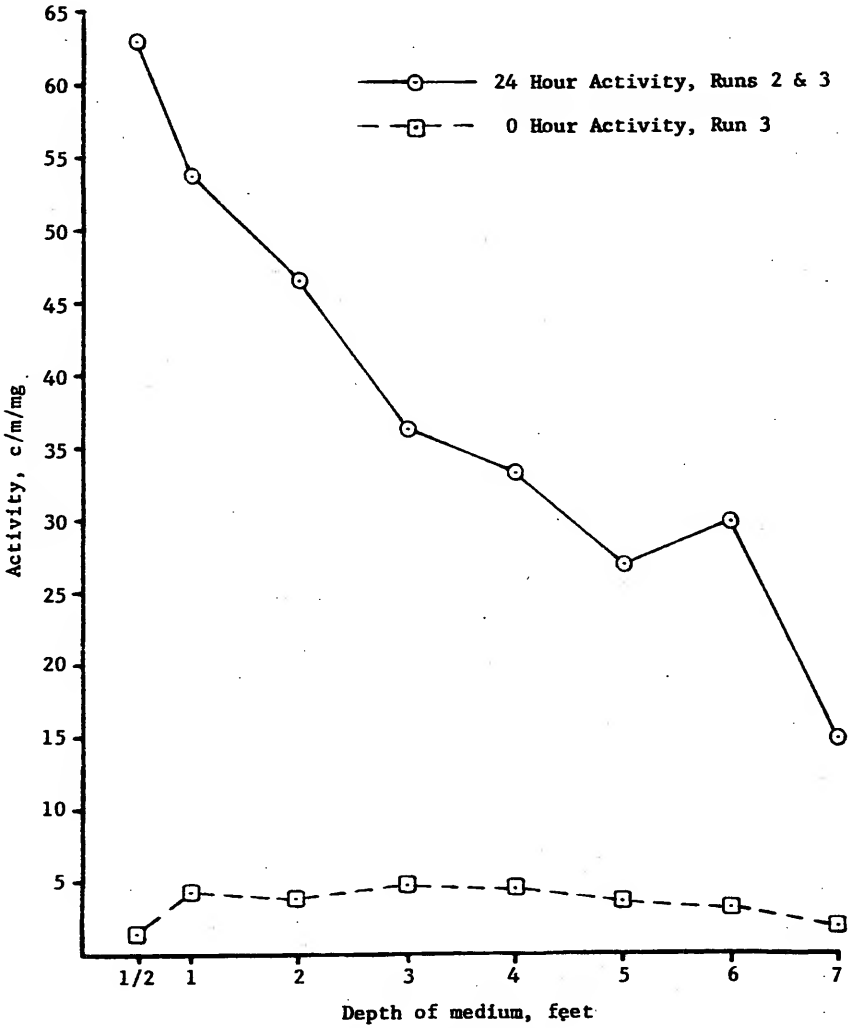

Fig. 16.- Activity of P-32 in filter slimes.

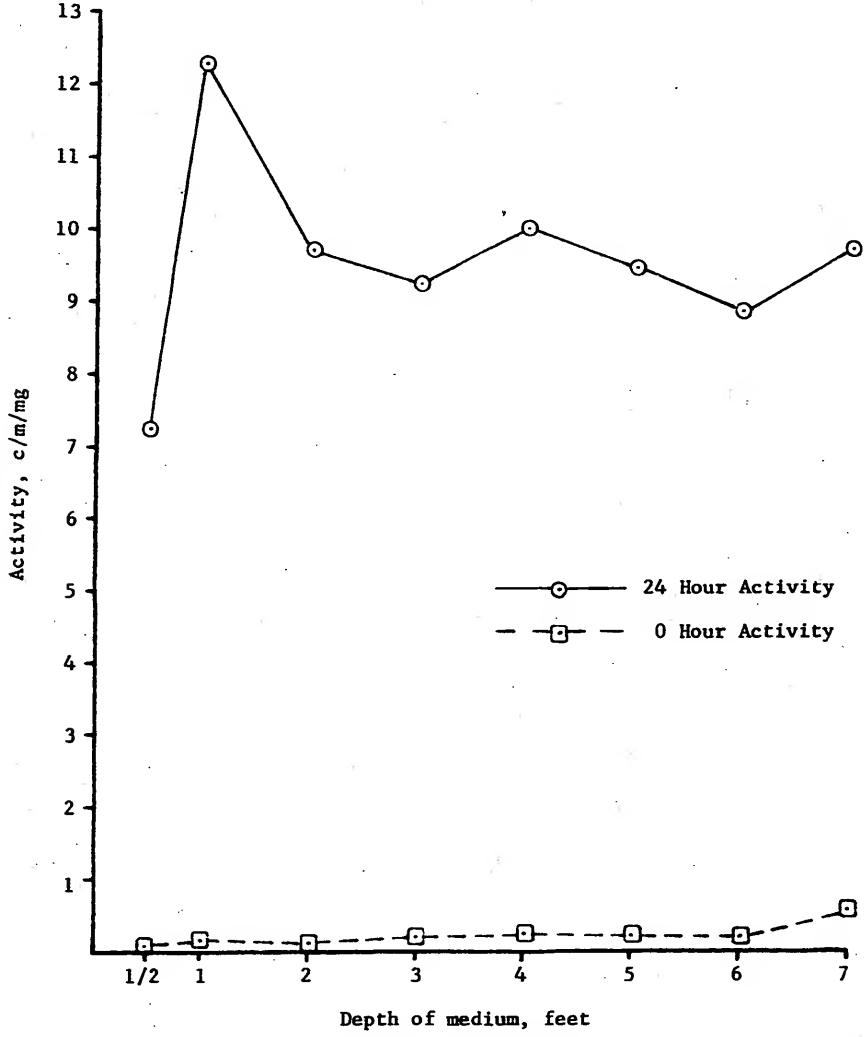

Fig. 17.- Activity of I-131 in filter slimes.

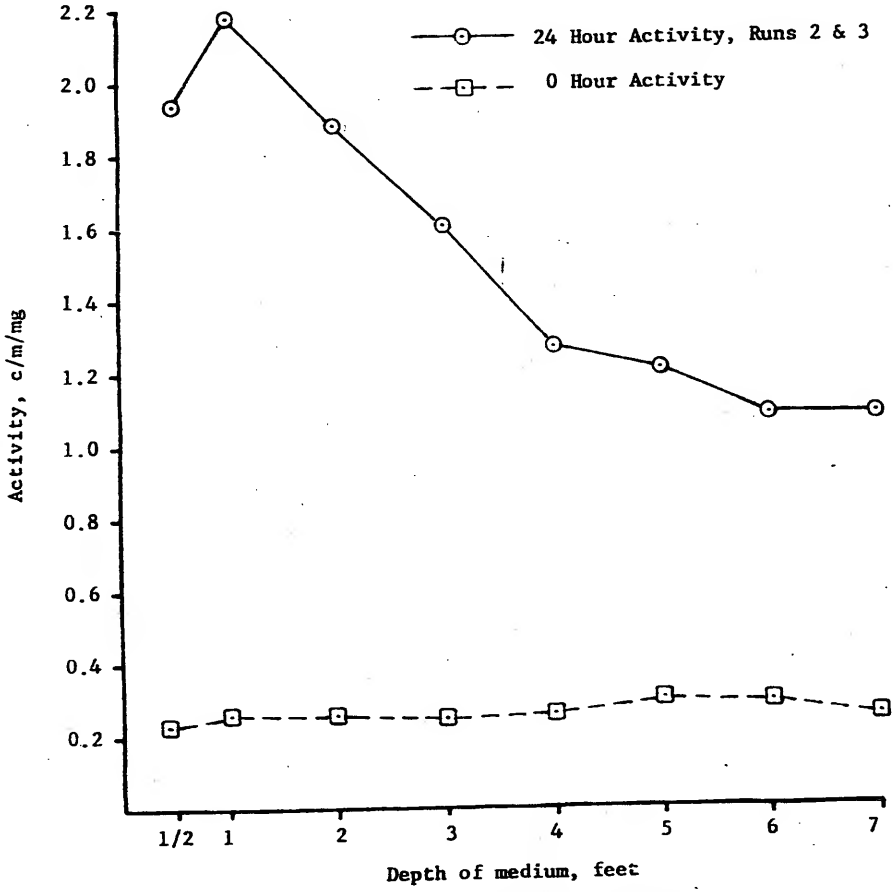

Fig. 18.- Activity of K-42 in filter slimes.

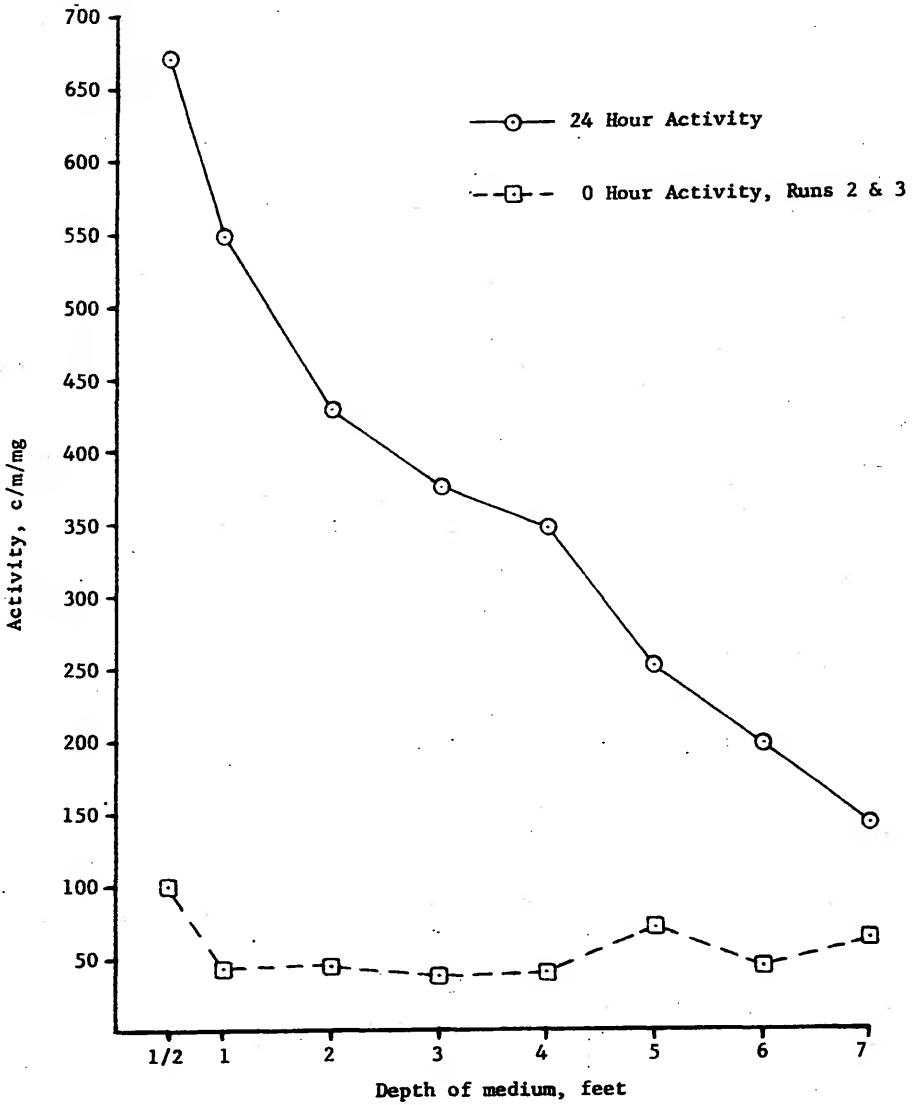

Fig. 19.- Activity of Ce-141, 144 in filter slimes.

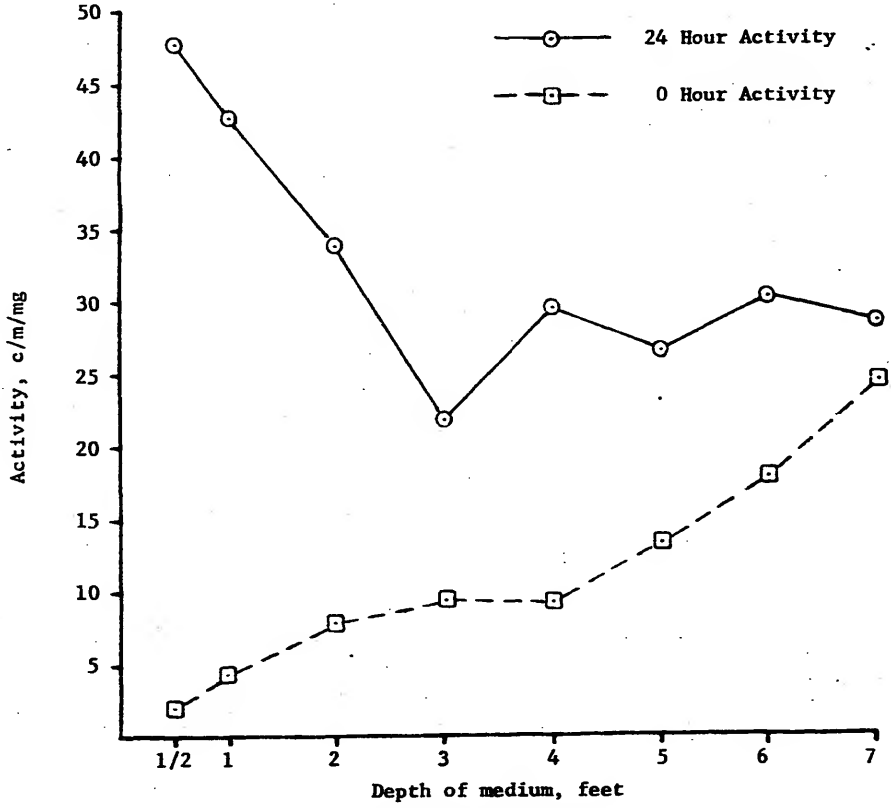

Fig. 20.- Activity of Fe-59 in filter slimes.

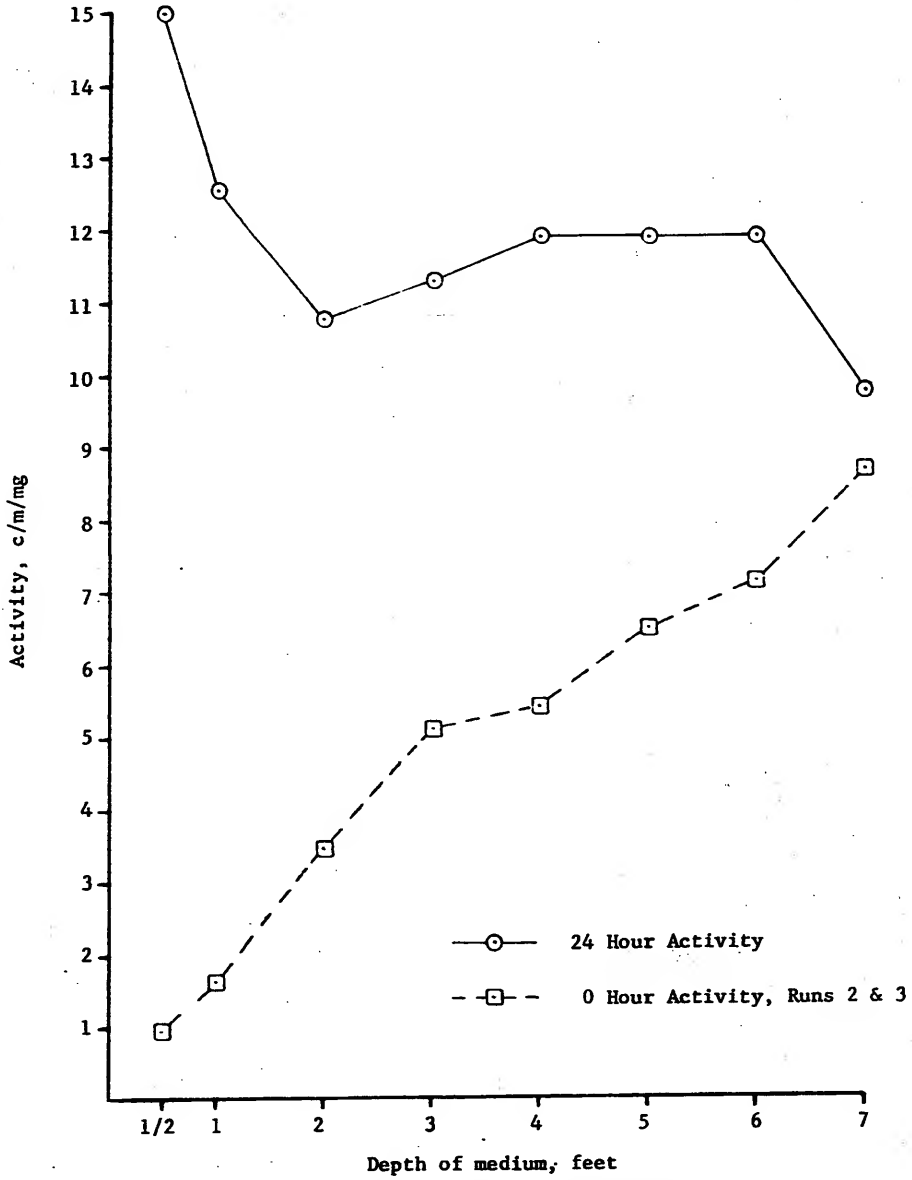

Fig. 21.- Activity of Co-58 in filter slimes.

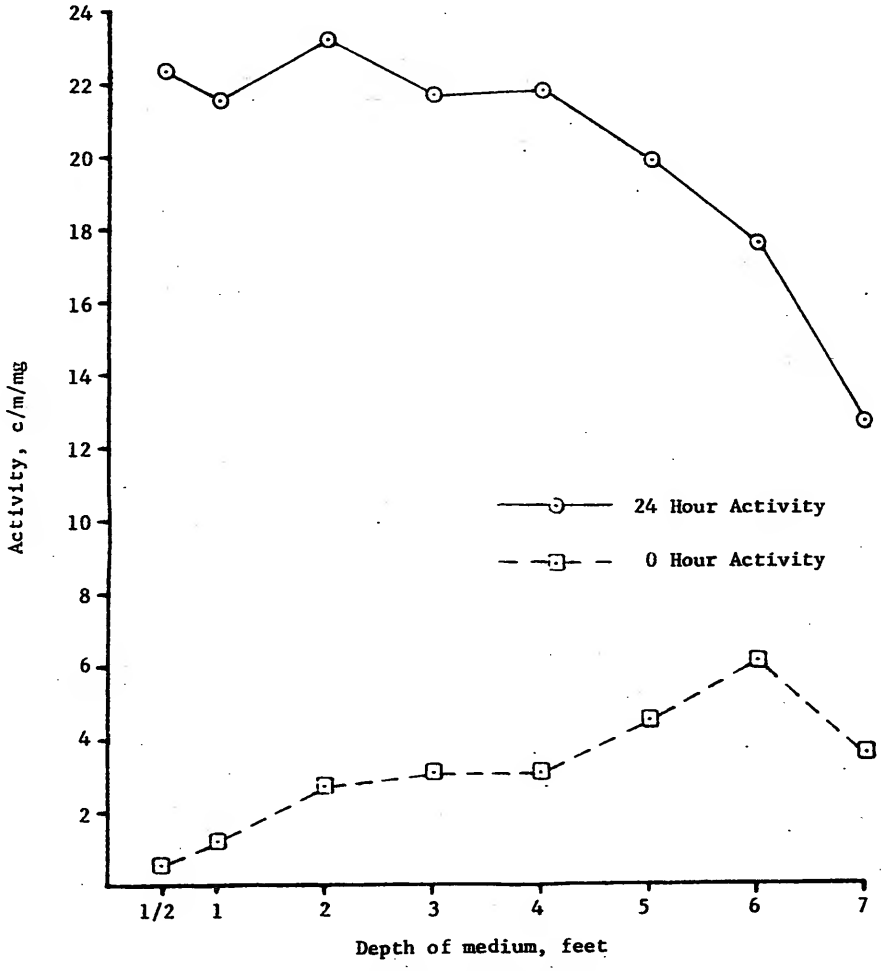

Fig. 22.- Activity of Sr-89 in filter slimes.

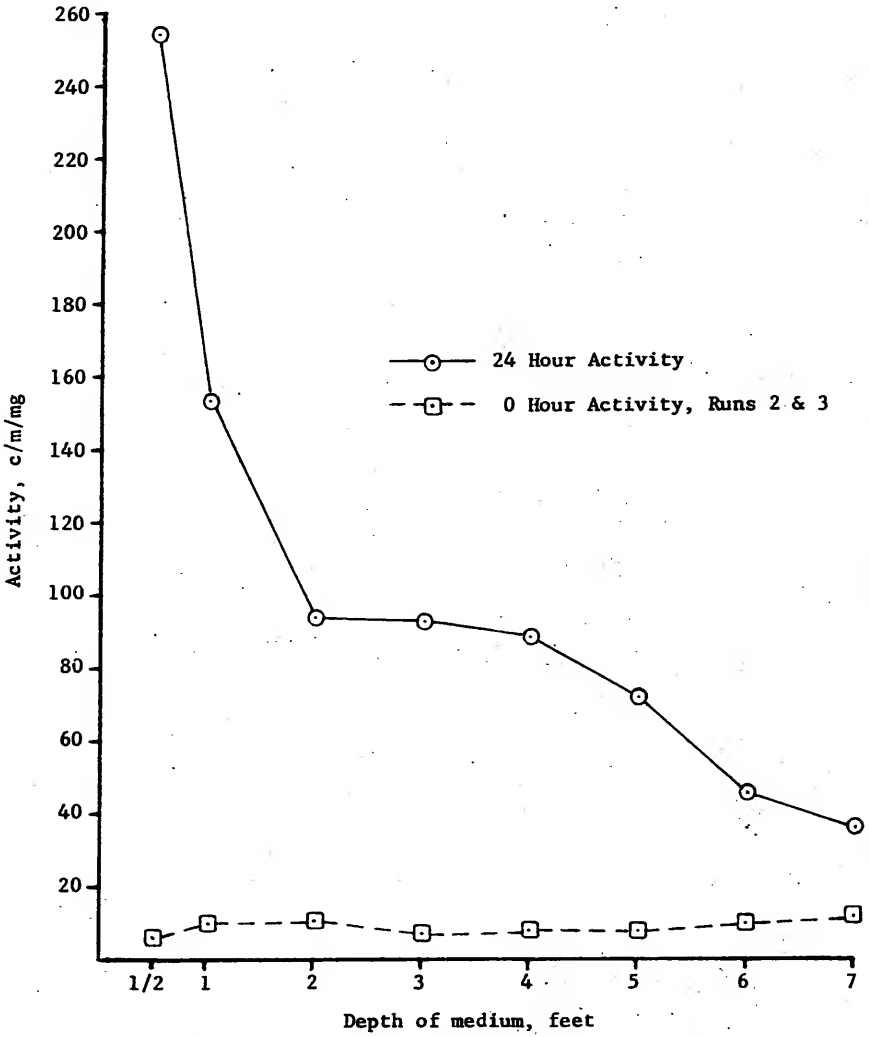

Fig. 23.- Activity of MFP in filter slimes.

TABLE 29

REMOVAL OF P-32 BY SECONDARY SEDIMENTATION

Time in Hours	Run 1			Run 2			Run 3			Average % Removal
	Infl. c/m	Eff. c/m	% Removal	Infl. c/m	Eff. c/m	% Removal	Infl. c/m	Eff. c/m	% Removal	
0	1.31	1.65	--	37.05	34.97	--	28.11	36.12	--	--
2	122.5	27.91	77.21	1010.	348.2	65.53	1422.	286.2	79.88	74.2
4	169.2	56.17	66.80	2184.	821.9	62.36	1972.	917.1	53.50	60.9
8	156.3	106.1	32.10	3431.	1915.	44.18	2159.	1561.	27.69	34.7
12	232.7	222.9	4.22	1805.	1828.	0.00	2229.	1894.	15.04	6.42
24	221.0	233.1	0.00	1453.	1500.	0.00	2080.	2054.	1.24	0.41

TABLE 30

REMOVAL OF I-131 BY SECONDARY SEDIMENTATION

Time in Hours	Run 1			Run 2			Run 3			Average % Removal
	Infl. c/m	Eff. c/m	% Removal	Infl. c/m	Eff. c/m	% Removal	Infl. c/m	Eff. c/m	% Removal	
0	6.64	7.83	--	3.50	2.87	--	1.13	0.51	--	--
2	160.1	80.69	49.60	188.9	80.67	57.29	155.7	64.73	58.44	55.1
4	194.7	119.5	38.60	157.7	102.0	35.33	188.2	131.7	30.02	34.6
8	229.7	196.1	14.66	149.1	135.8	8.87	187.8	158.4	15.67	13.1
12	214.5	204.4	4.72	185.1	172.5	6.79	182.3	192.3	0.00	3.84
24	176.6	171.6	2.82	136.8	141.9	0.00	159.2	148.8	6.55	3.12

TABLE 31

REMOVAL OF K-42 BY SECONDARY SEDIMENTATION

Time in Hours	Run 1			Run 2			Run 3			Average % Removal
	Infl. c/m	Eff. c/m	% Removal	Infl. c/m	Eff. c/m	% Removal	Infl. c/m	Eff. c/m	% Removal	
0	0.57	1.01	--	0.00	0.00	--	0.00	0.00	--	--
2	206.4	48.97	76.27	10.83	2.18	79.87	4.57	0.86	81.18	79.1
4	290.4	139.1	52.09	12.13	5.51	54.58	5.86	1.79	69.45	58.7
8	276.6	191.7	30.67	12.11	8.41	30.55	7.93	3.99	49.68	37.0
12	280.9	211.4	24.74	9.16	6.93	24.34	8.16	5.81	28.80	26.0
24	--	--	--	11.22	7.93	29.32	6.31	4.77	24.41	26.9

TABLE 32

REMOVAL OF Ce-141, 144 BY SECONDARY SEDIMENTATION

Time in Hours	Run 1			Run 2			Run 3			Average % Removal
	Infl. c/m	Eff. c/m	% Removal	Infl. c/m	Eff. c/m	% Removal	Infl. c/m	Eff. c/m	% Removal	
0	2.07	2.79	--	147.6	27.48	--	166.3	22.82	--	--
2	309.6	95.75	69.07	647.6	196.3	69.69	508.4	83.11	83.65	74.1
4	435.3	205.6	52.76	1096.	285.3	73.96	706.9	236.4	66.55	64.4
8	980.0	411.2	58.04	1413.	561.8	60.25	722.9	323.2	55.29	57.9
12	947.2	509.3	46.23	1466.	654.5	55.36	954.0	493.6	48.25	50.0
24	1006.	546.3	45.71	1436.	658.5	54.14	961.3	528.2	45.06	48.3

TABLE 33

REMOVAL OF Fe-59 BY SECONDARY SEDIMENTATION

Time in Hours	Run 1			Run 2			Run 3			Average % Removal
	Infl. c/m	Eff. c/m	% Removal	Infl. c/m	Eff. c/m	% Removal	Infl. c/m	Eff. c/m	% Removal	
0	24.06	8.85	--	95.12	22.55	--	81.88	12.41	--	--
2	204.0	31.25	84.64	151.3	26.47	82.50	103.3	14.85	85.63	84.3
4	177.4	34.63	80.48	157.0	33.28	78.81	136.9	26.99	80.29	79.9
8	176.2	42.32	75.98	132.2	46.88	64.55	152.2	43.48	71.44	70.7
12	211.5	53.68	74.62	148.8	48.90	67.13	122.9	49.64	59.62	67.1
24	208.3	55.88	73.18	212.7	66.25	68.86	172.0	53.09	69.12	70.4

TABLE 34

REMOVAL OF Co-58 BY SECONDARY SEDIMENTATION

Time in Hours	Run 1			Run 2			Run 3			Average % Removal
	Infl. c/m	Eff. c/m	% Removal	Infl. c/m	Eff. c/m	% Removal	Infl. c/m	Eff. c/m	% Removal	
0	39.89	3.38	--	33.48	7.90	--	39.88	5.14	--	--
2	43.70	9.03	79.34	44.12	11.38	74.21	47.66	7.65	83.95	79.2
4	70.16	12.57	82.08	53.90	11.72	78.26	67.95	10.16	85.05	81.8
8	64.01	26.01	59.37	64.86	26.07	59.81	77.32	26.17	66.15	61.8
12	68.77	25.78	62.51	--	--	--	73.18	24.82	66.08	64.3
24	62.82	22.60	64.03	68.27	24.27	64.42	66.58	24.42	63.32	63.9

TABLE 35

REMOVAL OF Sr-89 BY SECONDARY SEDIMENTATION

Time in Hours	Run 1			Run 2			Run 3			Average % Removal
	Infl. c/m	Eff. c/m	% Removal	Infl. c/m	Eff. c/m	% Removal	Infl. c/m	Eff. c/m	% Removal	
0	26.53	3.66	--	58.26	38.60	--	80.58	55.67	--	--
2	152.8	14.11	90.77	235.0	61.52	73.82	245.8	89.56	63.56	76.1
4	288.4	92.21	68.03	453.0	136.4	69.89	443.8	194.8	56.11	64.7
8	471.6	205.0	56.53	613.9	360.5	41.28	695.4	436.7	37.20	45.0
12	671.4	354.5	47.20	805.0	530.3	34.12	851.6	633.2	25.65	35.7
24	1103.	855.3	22.46	1328.	973.5	22.69	1196.	899.7	24.78	23.3

TABLE 36

REMOVAL OF MFP BY SECONDARY SEDIMENTATION

Time in Hours	Run 1			Run 2			Run 3			Average % Removal
	Infl. c/m	Eff. c/m	% Removal	Infl. c/m	Eff. c/m	% Removal	Infl. c/m	Eff. c/m	% Removal	
0	24.13	15.24	--	90.53	36.77	--	78.31	31.85	--	--
2	333.1	92.28	72.30	292.7	79.01	73.01	250.5	65.71	73.77	73.0
4	414.7	169.5	59.13	320.7	130.4	59.34	289.3	115.5	60.08	59.5
8	608.8	299.9	50.74	428.9	235.0	45.21	419.6	196.7	53.12	49.7
12	669.9	383.9	42.69	485.4	292.6	39.72	449.4	265.0	41.03	41.1
24	851.7	487.5	42.76	634.5	392.1	38.20	560.8	336.5	40.00	40.3

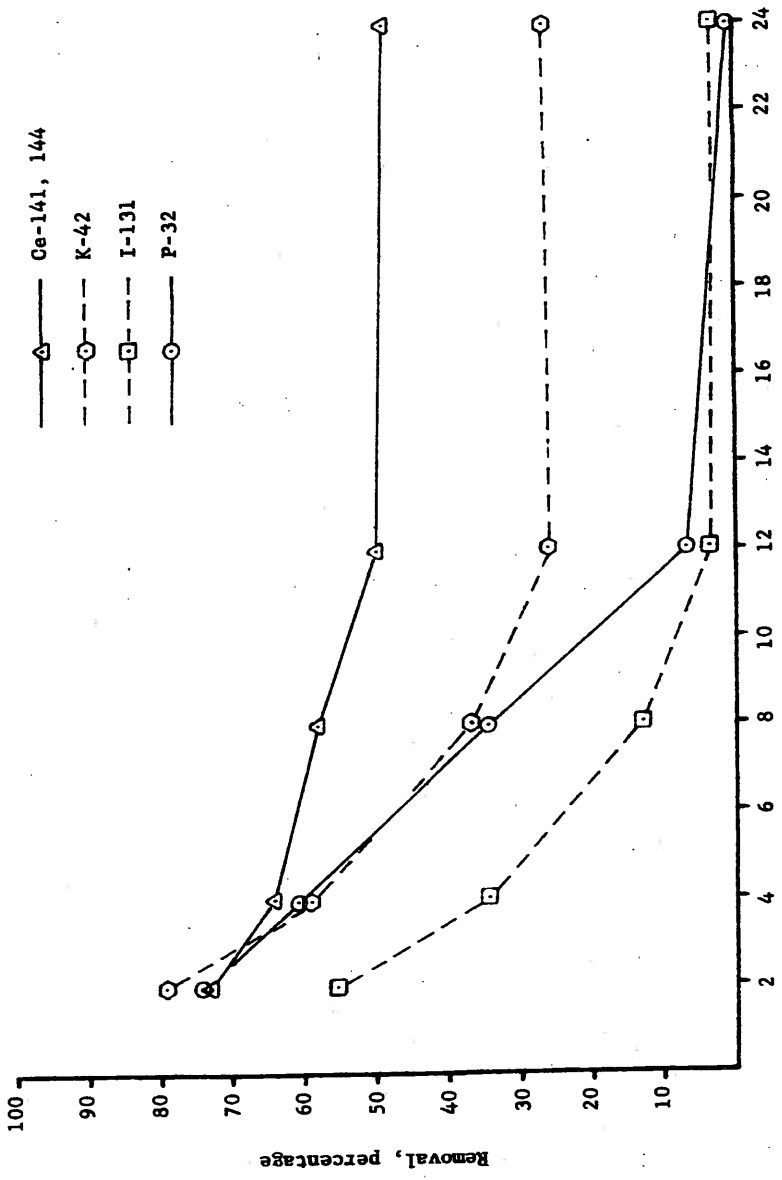

Fig. 24.- Removal of P-32, I-131, K-42, and Ce-141, 144 by secondary sedimentation.

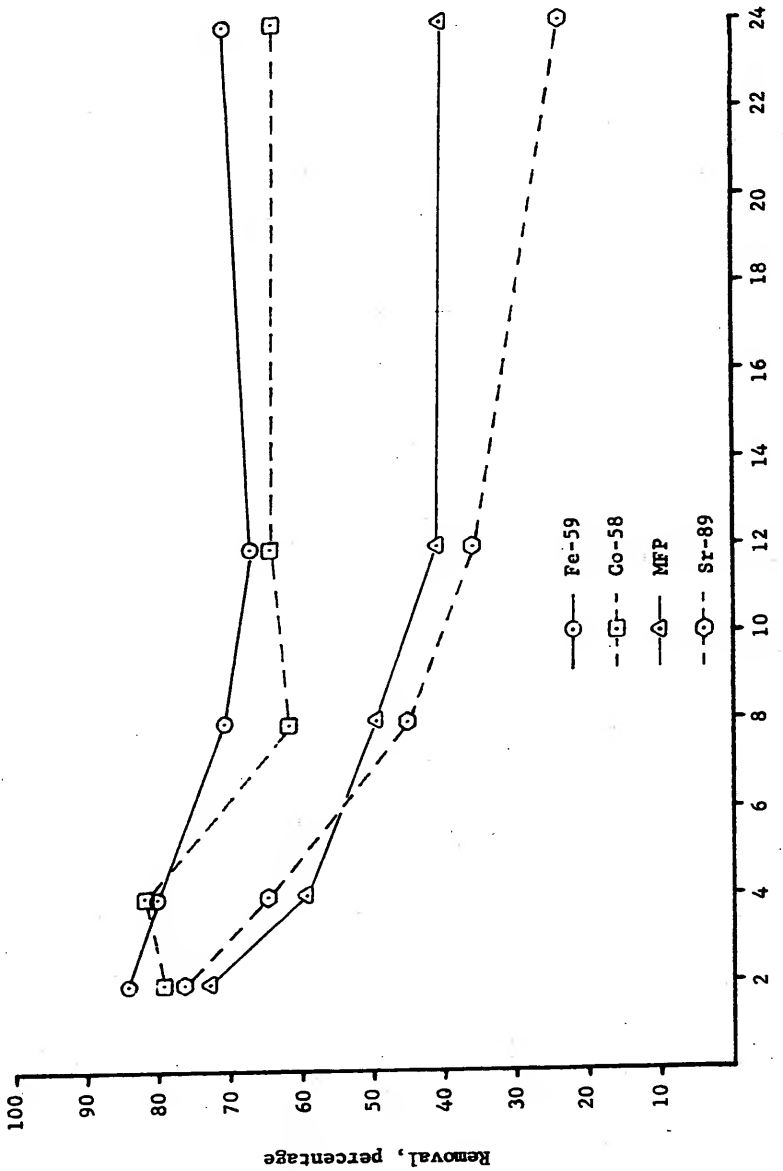

Fig. 25.- Removal of Fe-59, Co-58, Sr-89, and MFP by secondary sedimentation.

TABLE 37

ACTIVITY OF P-32 IN SECONDARY SLUDGE

Time in Hours	Activity (c/m/mg)			
	Run 1	Run 2	Run 3	Average
0	--	1.04	3.81	2.42
2	--	5.90	15.1	10.5
4	--	18.8	21.6	20.2
8	--	21.0	30.4	25.7
12	--	27.4	27.1	27.2
24	--	19.0	35.0	27.0

TABLE 38

ACTIVITY OF I-131 IN SECONDARY SLUDGE

Time in Hours	Activity (c/m/mg)			
	Run 1	Run 2	Run 3	Average
0	0.20	0.22	0.20	0.21
2	13.7	11.8	10.2	11.9
4	14.5	12.0	18.2	14.9
8	14.2	13.0	17.5	14.9
12	13.9	12.6	15.5	14.0
24	14.5	11.9	15.9	14.1

TABLE 39

ACTIVITY OF K-42 IN SECONDARY SLUDGE

Time in Hours	Activity (c/m/mg)			
	Run 1	Run 2	Run 3	Average Runs 2 & 3
0	0.70	0.37	0.38	0.38
2	15.7	1.23	0.74	0.98
4	20.3	1.16	0.73	0.94
8	25.2	1.41	0.96	1.18
12	--	1.34	1.03	1.18
24	--	1.59	1.07	1.33

TABLE 40

ACTIVITY OF Ce-141, 144 IN SECONDARY SLUDGE

Time in Hours	Activity (c/m/mg)			
	Run 1	Run 2	Run 3	Average Runs 2 & 3
0	0.18	89.0	108.	98.5
2	23.1	104.	131.	118.
4	46.0	159.	205.	182.
8	98.3	216.	227.	222.
12	107.	247.	272.	260.
24	124.	339.	271.	305.

TABLE 41

ACTIVITY OF Fe-59 IN SECONDARY SLUDGE

Time in Hours	Activity (c/m/mg)			
	Run 1	Run 2	Run 3	Average
0	6.70	26.9	24.1	19.2
2	29.8	34.9	31.5	32.1
4	32.0	40.2	34.3	35.5
8	34.9	47.2	40.2	40.8
12	39.8	47.3	43.4	43.5
24	54.4	67.0	64.7	62.0

TABLE 42

ACTIVITY OF Co-58 IN SECONDARY SLUDGE

Time in Hours	Activity (c/m/mg)			
	Run 1	Run 2	Run 3	Average
0	10.0	15.5	14.9	13.5
2	12.0	16.6	16.5	15.0
4	14.7	17.5	18.0	16.7
8	15.4	19.2	19.2	17.9
12	20.1	--	19.4	19.8
24	23.2	21.7	23.4	22.8

TABLE 43

ACTIVITY OF Sr-89 IN SECONDARY SLUDGE

Time in Hours	Activity (c/m/mg)			
	Run 1	Run 2	Run 3	Average
0	8.25	8.68	3.42	6.78
2	10.7	10.9	4.08	8.56
4	12.3	13.8	7.38	11.2
8	16.9	18.9	15.2	17.0
12	20.8	25.1	19.4	21.8
24	28.0	32.7	23.1	27.9

TABLE 44

ACTIVITY OF MFP IN SECONDARY SLUDGE

Time in Hours	Activity (c/m/mg)			
	Run 1	Run 2	Run 3	Average
0	5.01	23.1	20.9	16.3
2	50.8	44.6	38.7	44.7
4	57.2	47.8	41.3	48.8
8	59.9	51.4	44.4	51.9
12	65.5	58.7	49.9	58.0
24	67.1	71.0	53.8	64.0

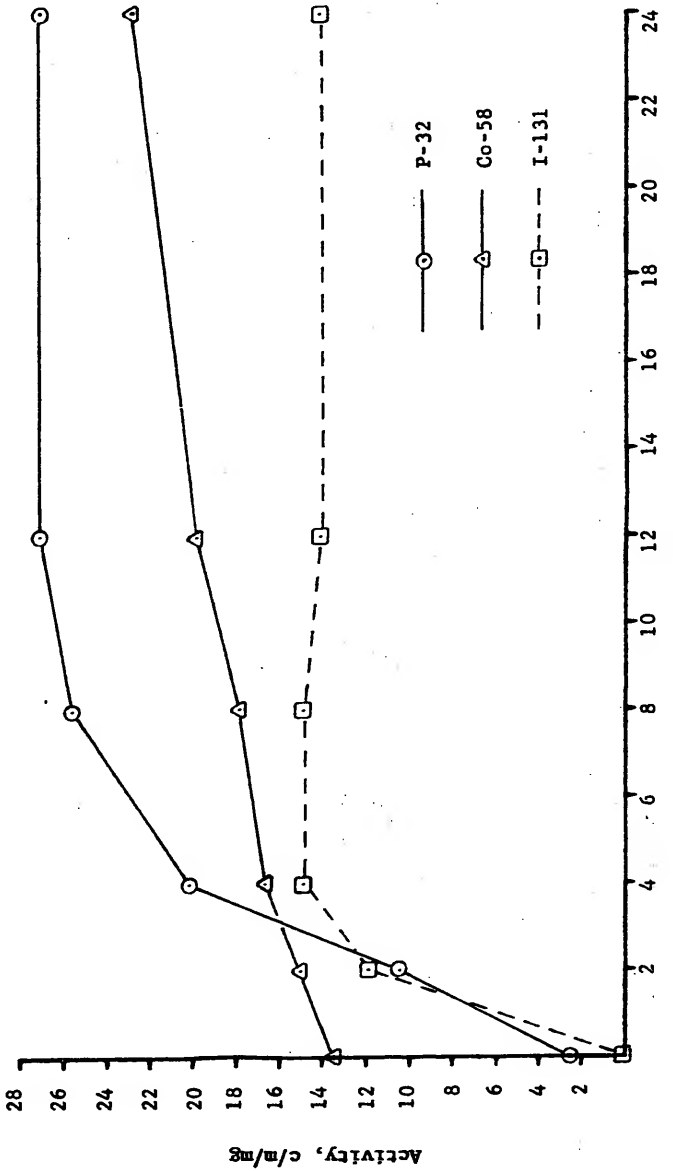

Fig. 26.- Activity of P-32, I-131, and Co-58 in secondary sludge.

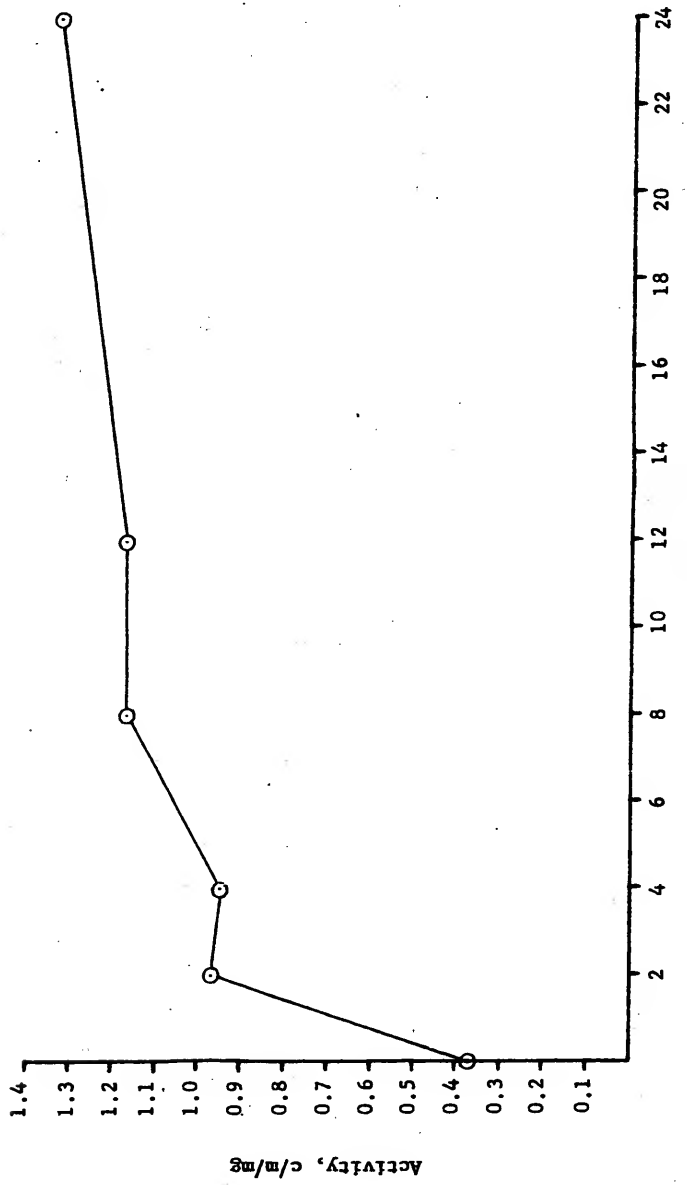

Fig. 27.- Activity of K-42 in secondary sludge.

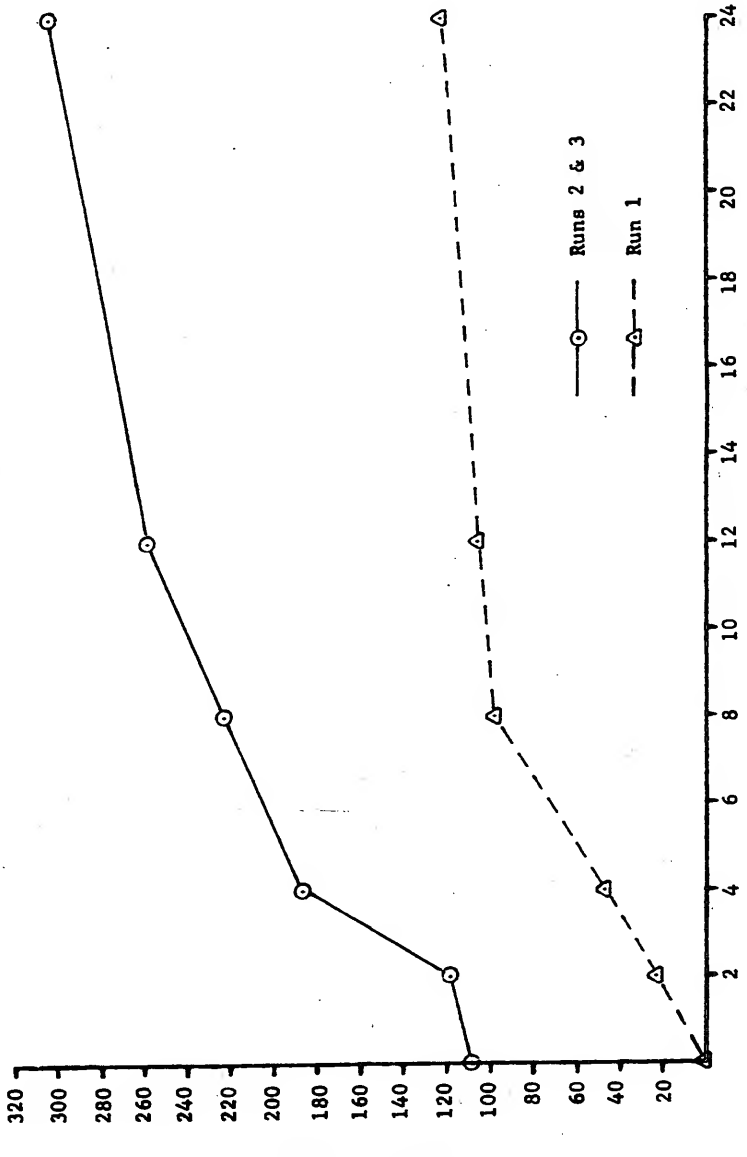

Fig. 28.- Activity of Ce-141, 144 in secondary sludge.

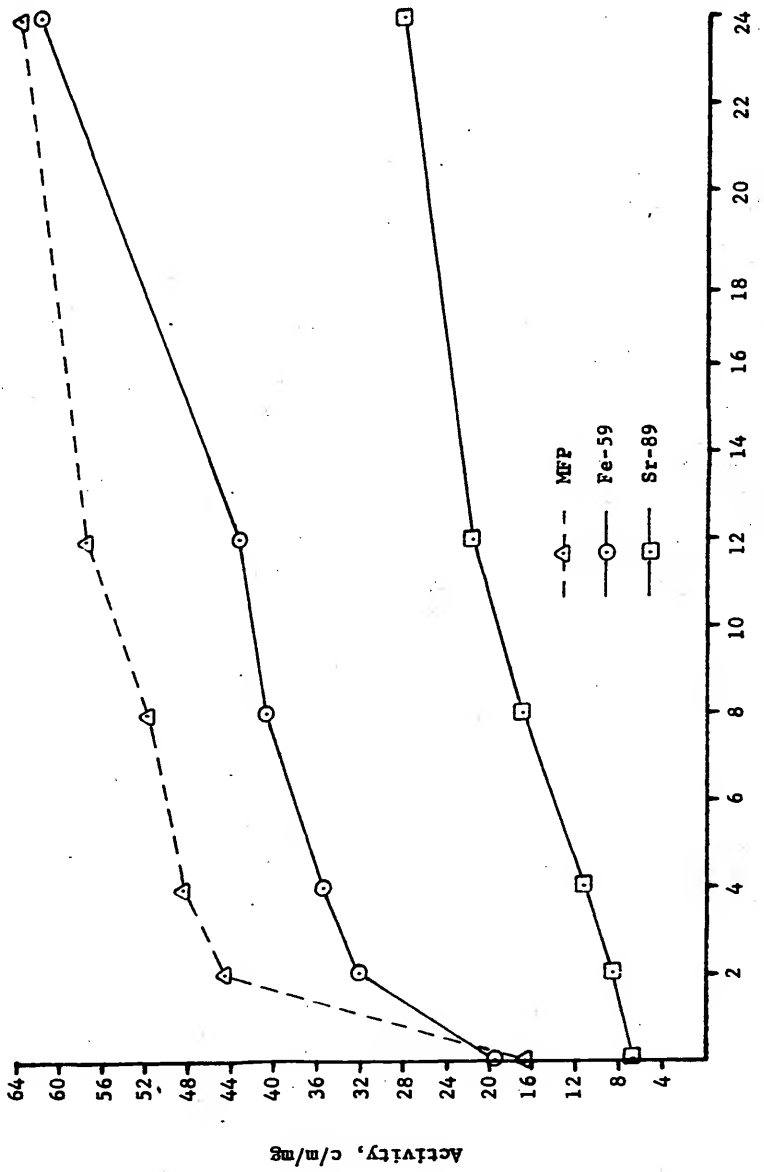

Fig. 29.- Activity of Fe-59, Sr-89, and MFP in secondary sludge.

APPENDIX F

TABULATED DATA AND GRAPHS -- REMOVAL OF SELECTED RADIONUCLIDES BY LAGOONING

TABLE 45

REMOVAL OF P-32 BY LAGOONING

Time in Days	Activity (c/m)					
	Run 1		Run 2		Run 3	
	Infl.	Eff.	Infl.	Eff.	Infl.	Eff.
0	1.65	1.60	30.90	17.79	36.93	109.2
1	247.1	4.77	1542.	26.84	2069.	105.6
2	279.1	55.07	311.9	175.5	251.0	201.0
3	48.10	65.31	162.4	224.3	118.4	293.7
4	25.72	58.89	78.76	242.8	91.71	297.5
5	10.55	55.06	58.75	198.1	62.38	241.0
6	11.55	41.52	43.39	141.8	60.89	202.6

TABLE 46

REMOVAL OF I-131 BY LAGOONING

Time in Days	Activity (c/m)					
	Run 1		Run 2		Run 3	
	Infl.	Eff.	Infl.	Eff.	Infl.	Eff.
0	9.04	25.71	3.91	20.36	1.54	13.59
1	178.4	29.69	160.2	23.19	135.6	14.04
2	18.14	53.06	12.38	57.28	8.99	38.04
3	9.63	62.80	8.75	37.87	5.03	33.32
4	7.05	45.88	4.03	33.85	3.86	29.01
5	5.51	39.40	4.35	30.45	1.78	22.86
6	4.46	27.06	4.08	20.71	2.64	17.59

TABLE 47

REMOVAL OF Ce-141, 144 BY LAGOONING

Time in Days	Activity (c/m)					
	Run 1		Run 2		Run 3	
	Infl.	Eff.	Infl.	Eff.	Infl.	Eff.
0	3.64	3.16	127.0	4.44	33.76	6.17
1	295.3	3.83	359.3	3.76	330.0	6.34
2	250.2	13.28	413.0	15.56	121.1	17.95
3	149.0	18.91	264.8	23.47	52.52	23.11
4	70.59	8.53	177.3	20.14	50.87	18.54
5	55.76	8.47	99.65	14.50	61.20	11.86
6	54.49	4.28	51.99	9.71	74.13	10.53

TABLE 48

REMOVAL OF Fe-59 BY LAGOONING

Time in Days	Activity (c/m)					
	Run 1		Run 2		Run 3	
	Infl.	Eff.	Infl.	Eff.	Infl.	Eff.
0	14.14	5.41	18.42	2.32	17.79	4.64
1	72.06	6.50	78.74	2.59	65.31	5.30
2	59.61	6.95	39.88	4.48	38.18	6.06
3	49.49	7.38	32.45	3.66	16.59	5.27
4	39.42	6.26	36.04	3.72	22.60	4.41
5	29.41	6.50	30.34	3.83	14.47	3.41
6	11.63	5.44	24.58	3.88	14.60	5.51

TABLE 49

REMOVAL OF Co-58 BY LAGOONING

Time in Days	Activity (c/m)					
	Run 1		Run 2		Run 3	
	Infl.	Eff.	Infl.	Eff.	Infl.	Eff.
0	6.40	3.17	7.17	7.35	5.88	4.87
1	23.30	3.02	24.08	5.50	23.70	3.19
2	10.42	4.08	13.38	6.14	17.88	7.01
3	11.78	5.94	10.31	6.90	13.64	6.72
4	12.01	6.75	11.33	6.18	13.15	7.09
5	--	--	12.76	4.79	13.27	6.14
6	7.16	6.91	9.12	5.38	11.14	5.80

TABLE 50

REMOVAL OF Sr-89 BY LAGOONING

Time in Days	Activity (c/m)					
	Run 1		Run 2		Run 3	
	Infl.	Eff.	Infl.	Eff.	Infl.	Eff.
0	6.40	4.40	42.52	54.27	56.27	85.84
1	747.6	4.43	1000.	41.89	969.9	76.12
2	395.9	26.97	476.7	92.08	408.6	91.20
3	173.5	49.36	225.4	94.24	211.2	144.7
4	120.5	57.50	155.1	104.9	126.9	149.2
5	66.05	53.29	90.16	104.7	94.34	142.0
6	55.12	51.64	73.42	91.20	--	--

TABLE 51

REMOVAL OF MFP BY LAGOONING

Time in Days	Activity (c/m)					
	Run 1		Run 2		Run 3	
	Infl.	Eff.	Infl.	Eff.	Infl.	Eff.
0	16.05	44.31	50.93	49.46	35.52	41.66
1	491.1	47.76	413.0	53.05	442.6	46.82
2	191.9	53.09	148.9	49.05	206.4	51.33
3	102.7	59.51	87.48	66.27	108.5	66.35
4	61.96	62.81	72.63	57.00	87.28	68.13
5	--	--	62.97	58.31	68.05	55.82
6	51.98	57.58	48.88	54.57	36.72	58.46

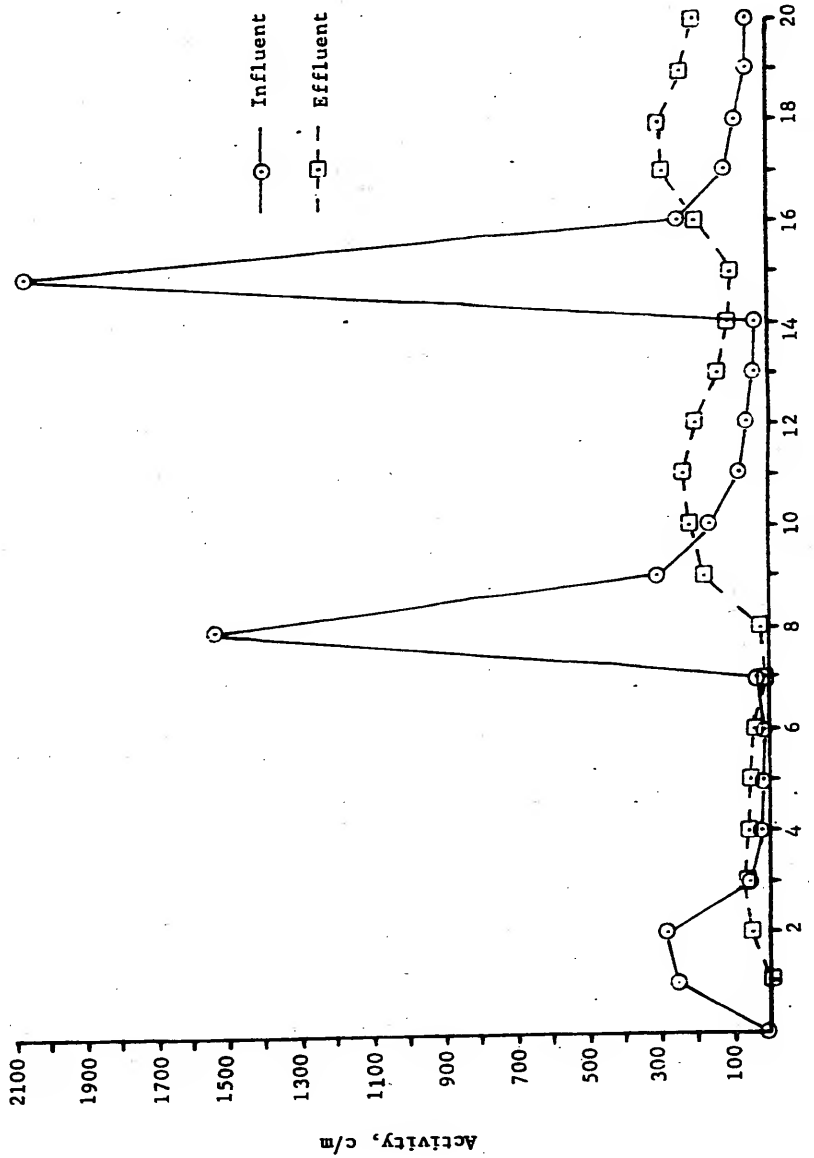

Fig. 30.- Removal of P-32 by lagooning.

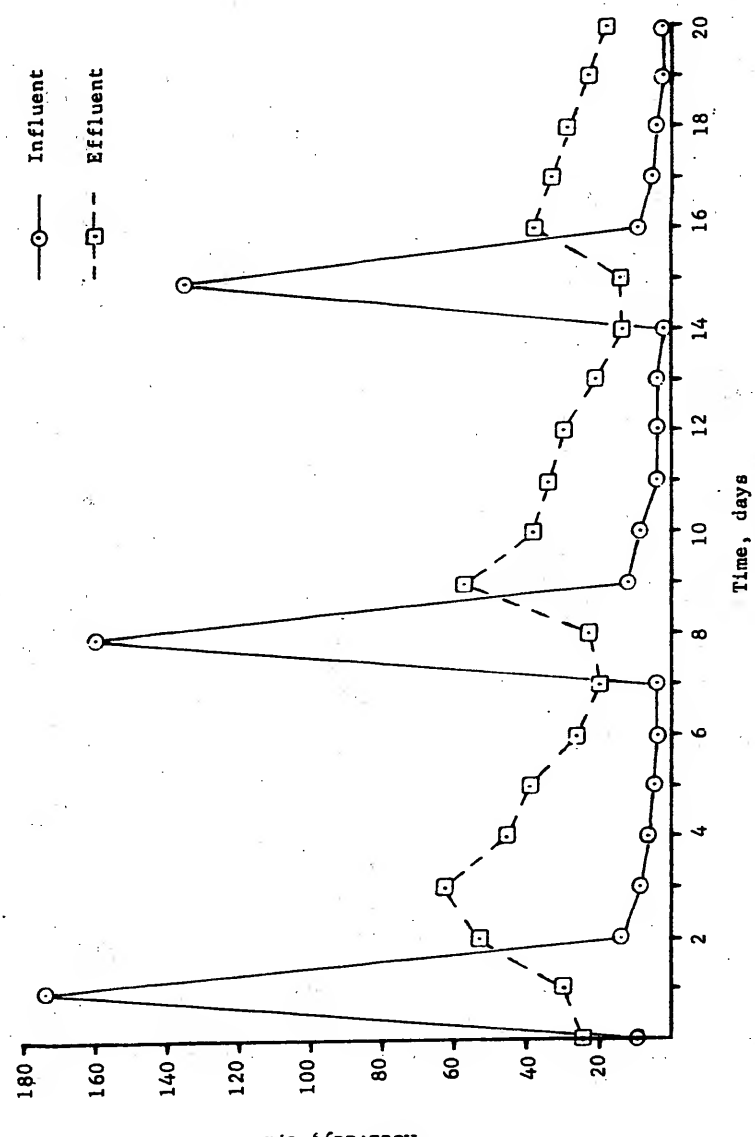

Fig. 31.- Removal of I-131 by lagooning.

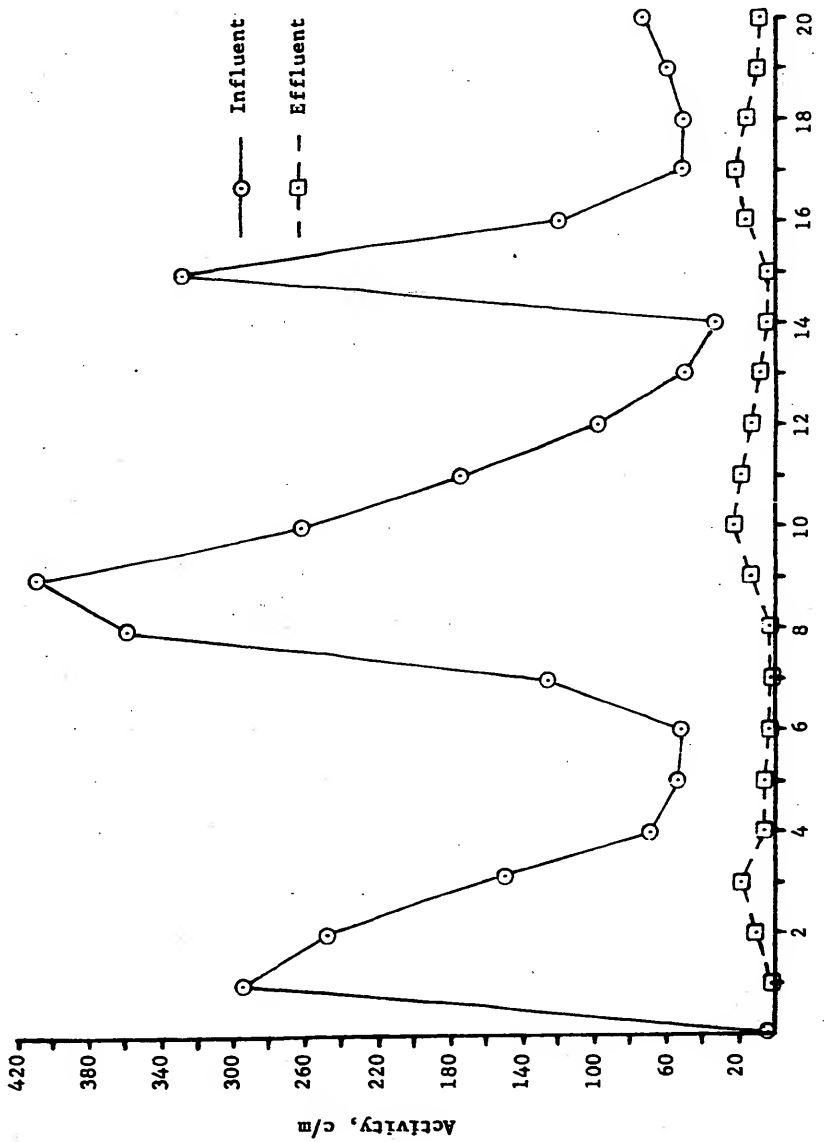

Fig. 32.- Removal of Ce-141, 144 by lagooning.

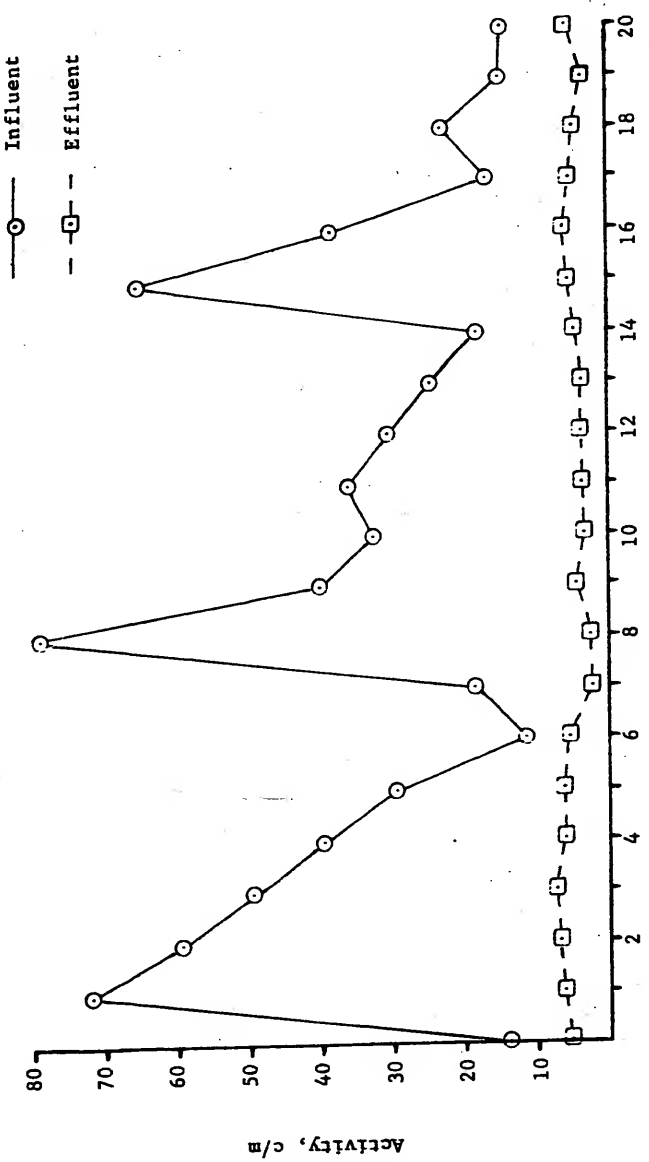

Fig. 33.- Removal of Fe-59 by lagooning.

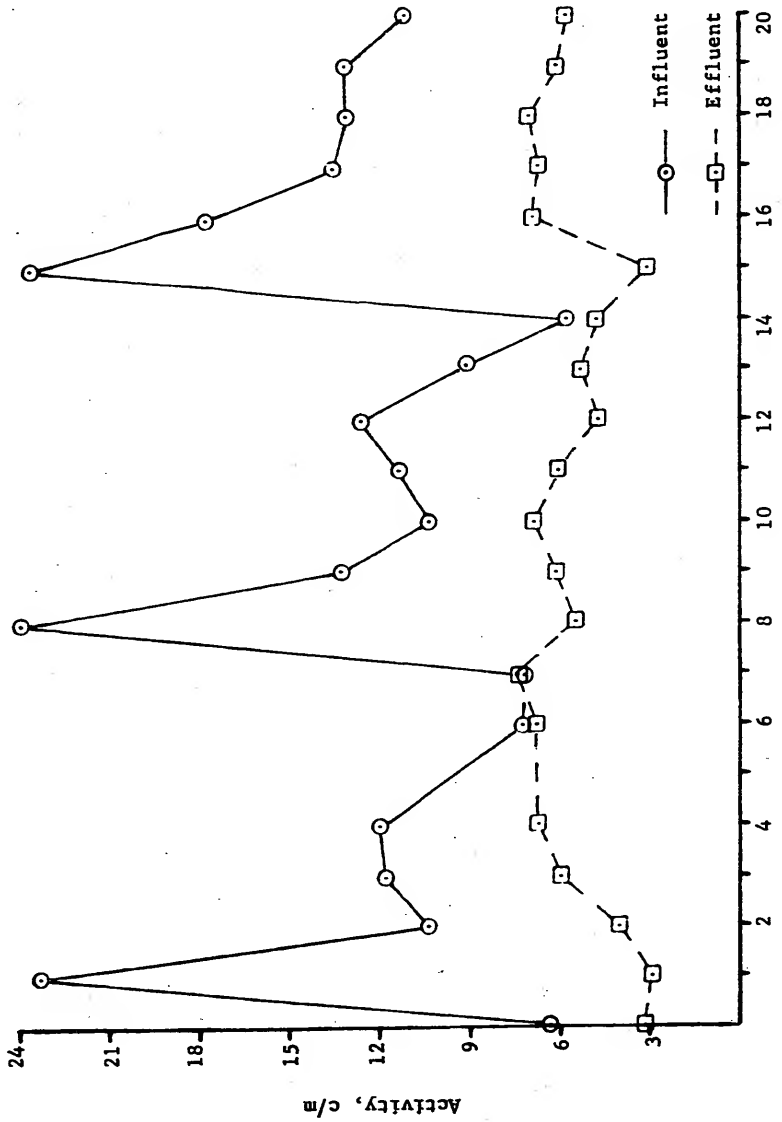

Fig. 34.- Removal of Co-58 by lagooning.

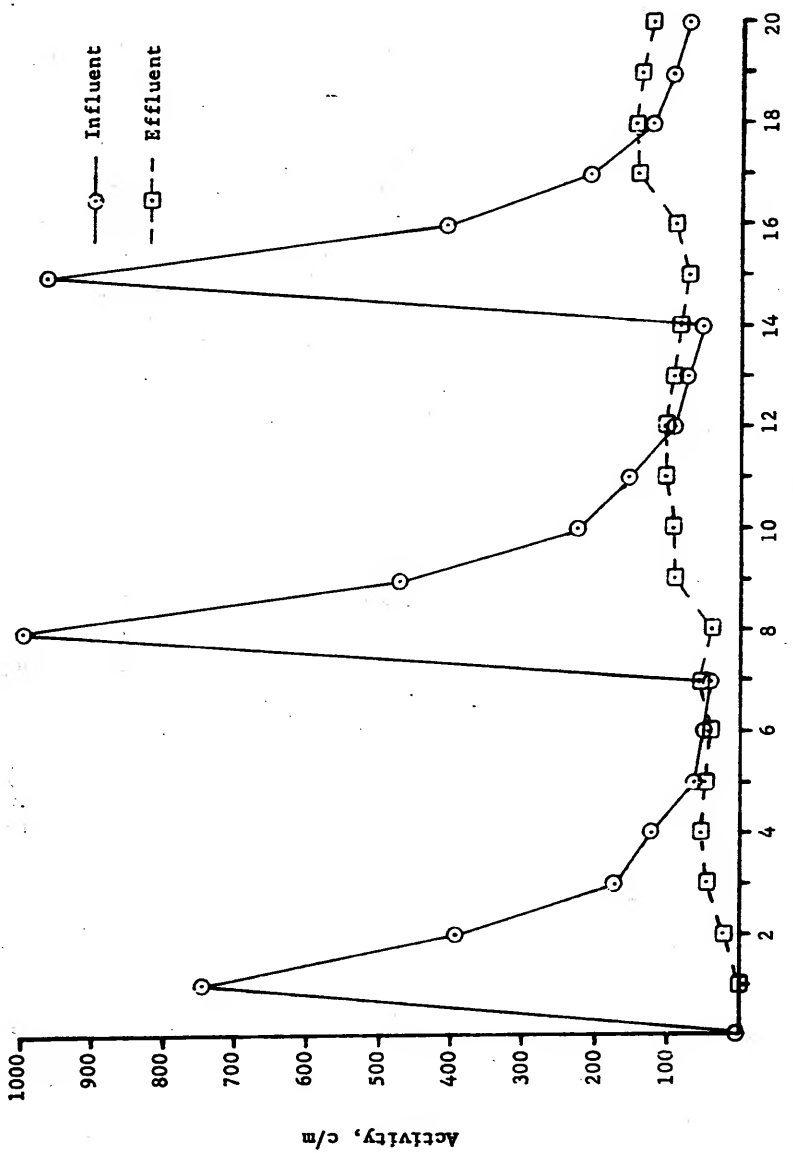

Fig. 35.- Removal of Sr-89 by lagooning.

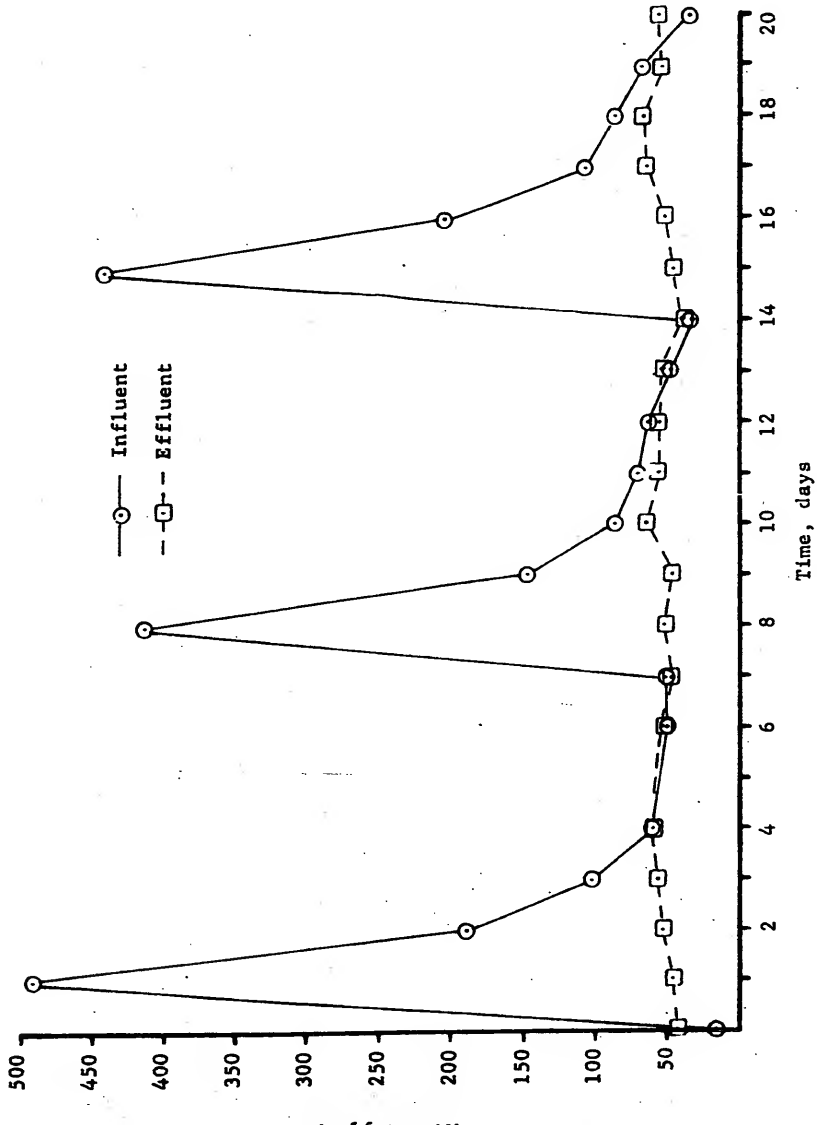

Fig. 36.- Removal of MFP by lagooning.

APPENDIX G

TABULATED DATA -- RESULTS OF CHEMICAL AND BIOCHEMICAL ANALYSES

TABLE 52

PRIMARY SEDIMENTATION BASIN DATA

BOD and Suspended Solids Analyses

Date	BOD			Total Suspended Solids			Volatile Suspended Solids		
	Infl. (mg/l)	Eff. (mg/l)	% Removal	Infl. (mg/l)	Eff. (mg/l)	% Removal	Infl. (mg/l)	Eff. (mg/l)	% Removal
3-4	--	--	--	207	102	50.7	176	88.0	50.0
3-13	114	50.8	55.6	139	65.0	53.2	108	54.0	50.0
3-21	179	87.5	51.1	--	--	--	--	--	--
4-11	126	99.0	21.5	95.0	61.0	35.8	75.0	21.0	72.0
4-18	179	116	35.2	205	103	49.8	161	77.0	52.2
4-25	189	140	25.9	124	85.0	31.5	106	65.0	38.8
5-10	222	188	15.3	172	95.0	44.8	146	78.0	46.6
5-20	--	--	--	113	71.0	37.2	89.0	66.0	23.3
6-3	177	161	9.04	180	79.0	56.1	158	75.0	52.5
6-10	181	131	27.6	139	64.0	54.0	121	59.0	51.2

TABLE 52 -- (Continued)

Date	BOD			Total Suspended Solids			Volatile Suspended Solids		
	Infl. (mg/l)	Eff. (mg/l)	% Removal	Infl. (mg/l)	Eff. (mg/l)	% Removal	Infl. (mg/l)	Eff. (mg/l)	% Removal
6-17	180	127	29.5	116	68.0	41.4	114	60.0	47.4
7-8	165	140	15.2	108	72.0	33.3	96.0	65.0	32.3
7-15	225	156	30.7	99.0	72.0	27.3	80.0	52.0	35.0
7-22	196	137	30.1	119	68.0	42.9	98.0	48.0	51.0
8-15	138	86.9	37.0	144	61.0	57.6	131	61.0	53.4
8-19	154	90.5	41.2	156	149	4.49	144	145	0.0
8-26	173	131	24.3	96.0	67.0	30.2	89.0	64.0	28.1
9-9	170	143	15.9	103	60.0	41.7	82.0	47.0	42.7
9-16	144	114	20.8	154	79.0	48.7	30.0	27.0	10.0
9-23	144	108	25.0	105	65.0	38.1	81.0	51.0	37.0
Average	170	--	28.4	135	--	41.0	--	--	40.7

TABLE 53

TRICKLING FILTER DATA

BOD in mg/l by Depth and Date

Date	0'	1/2'	1'	2'	3'	4'	5'	6'	7'	8'
3-4	61.0	36.8	31.2	28.9	15.4	15.9	13.3	15.5	13.3	8.40
3-13	27.4	--	17.5	11.4	10.2	8.77	9.50	12.1	8.70	--
3-21	35.6	27.1	20.6	18.8	15.9	9.31	7.57	7.65	8.41	5.85
4-11	55.3	35.0	25.3	15.3	9.51	7.61	6.10	7.08	5.23	5.10
4-18	64.4	50.2	44.8	36.2	23.4	15.6	13.2	7.40	6.87	12.1
4-25	43.7	27.2	19.7	14.5	12.4	10.3	4.64	5.43	4.35	4.64
5-10	108.	80.5	53.6	38.4	26.9	18.3	15.3	9.97	11.9	9.98
5-20	115.	--	60.4	--	39.1	29.4	16.2	16.3	14.0	12.1
6-3	81.7	41.5	38.1	30.7	20.2	24.5	11.9	10.5	14.0	6.38
6-10	36.0	25.6	23.0	20.8	14.8	11.1	8.75	6.80	5.21	5.05

TABLE 53 -- (Continued)

Date	0'	1/2'	1'	2'	3'	4'	5'	6'	7'	8'
6-17	83.8	45.2	37.4	23.9	20.4	17.9	8.70	8.51	7.84	7.87
7-8	121.	93.9	80.2	49.6	38.3	35.4	22.6	21.3	17.8	16.1
7-15	103.	52.2	37.3	--	--	25.1	17.5	13.2	10.8	9.13
7-22	80.1	60.2	52.7	9.15	12.7	10.6	5.67	7.44	4.92	5.76
8-15	48.8	27.3	20.5	15.0	10.9	7.02	6.32	4.79	4.97	4.54
8-19	61.3	30.4	24.7	17.0	13.8	10.1	9.42	7.29	7.34	7.28
8-26	36.1	21.3	15.9	14.1	10.5	8.64	6.26	6.82	6.02	6.40
9-9	83.8	44.5	33.4	22.9	16.2	11.8	7.41	7.86	6.08	7.28
9-16	139.	74.8	55.4	34.2	21.4	15.7	11.8	10.5	7.44	9.61
9-23	80.6	48.0	35.8	24.4	16.8	14.3	9.14	6.25	6.54	7.73

TABLE 54

TRICKLING FILTER DATA

Percentage Reduction in BOD by Depth and Date

Date	1/2'	1'	2'	3'	4'	5'	6'	7'	8'
3-4	39.7	48.9	57.7	74.8	73.9	78.2	74.6	78.2	86.2
3-13	--	36.1	58.4	62.8	68.0	65.3	--	--	--
3-21	23.8	42.2	47.2	55.3	73.8	78.7	78.5	76.4	83.5
4-11	36.7	54.3	72.3	82.8	86.2	89.0	87.2	90.5	90.8
4-18	22.0	30.4	43.8	63.7	75.8	79.5	88.5	89.3	81.2
4-25	37.7	55.0	66.8	71.6	76.4	89.4	87.6	90.0	89.4
5-10	25.5	50.4	64.5	75.1	83.0	85.7	90.8	89.0	90.8
5-20	--	47.5	--	66.0	74.4	85.9	85.7	87.8	89.5
6-3	49.2	53.4	62.4	75.3	70.0	85.4	87.1	82.9	92.9
6-10	28.9	36.1	42.2	58.9	69.2	75.7	81.1	85.5	86.0

TABLE 54 -- (Continued)

Date	1/2'	1'	2'	3'	4'	5'	6'	7'	8'
6-17	46.0	55.4	71.5	75.6	78.6	89.6	89.8	90.6	90.6
7-8	22.4	33.7	59.0	68.3	70.7	81.3	82.4	85.3	86.7
7-15	49.3	63.8	--	--	75.6	83.0	87.2	89.5	91.1
7-22	24.8	34.2	88.6	84.1	86.8	92.9	90.7	93.9	92.8
8-15	44.1	58.0	69.3	77.7	85.6	87.0	90.2	89.8	90.7
8-19	50.4	59.7	72.3	77.5	83.5	84.6	88.1	88.0	88.1
8-26	41.0	56.0	60.9	70.9	76.1	82.7	81.1	83.3	82.3
9-9	46.9	60.1	72.7	80.7	85.9	91.2	90.6	92.7	91.3
9-16	46.2	60.1	75.4	84.6	88.7	91.5	92.4	95.6	93.1
9-23	40.4	55.6	69.7	79.2	82.3	88.7	92.2	91.9	90.4
Average	37.5	49.5	64.2	72.9	78.2	84.3	86.6	87.9	88.8

TABLE 55

TRICKLING FILTER DATA

Total Nitrogen in mg/l by Depth and Date

Date	0'	1/2'	1'	2'	3'	4'	5'	6'	7'	8'
3-4	18.8	--	--	--	12.0	7.00	--	--	5.88	--
3-13	15.1	--	11.5	9.52	8.96	6.16	4.48	3.08	2.52	1.96
3-21	16.5	14.9	14.0	13.2	9.96	7.84	7.28	6.24	5.32	3.64
4-11	11.4	9.44	8.60	7.20	6.64	3.08	2.94	1.82	1.62	1.62
4-18	11.3	9.24	8.57	7.44	7.28	4.20	3.92	1.96	1.96	1.68
4-25	14.5	13.6	12.7	9.78	8.79	6.44	4.30	3.58	4.48	3.08
5-10	16.0	12.9	--	10.1	7.84	4.76	4.07	3.08	2.24	2.24
5-20	18.5	17.9	15.7	11.6	8.96	5.88	4.76	3.36	3.36	2.52
6-3	15.4	12.8	11.5	9.50	7.00	4.76	3.92	3.64	1.68	1.68
6-10	14.3	13.0	11.5	9.24	6.73	3.92	2.24	2.24	1.96	1.12

TABLE 55 -- (Continued)

Date	0'	1/2'	1'	2'	3'	4'	5'	6'	7'	8'
6-17	14.0	12.5	11.2	8.32	7.00	5.04	3.64	2.94	2.13	1.96
7-8	19.5	16.3	15.1	12.0	9.80	6.86	4.90	4.20	3.50	2.80
7-15	15.2	14.1	11.3	8.59	6.44	7.14	4.70	4.76	2.52	2.80
7-22	12.0	11.2	9.30	6.66	5.46	3.64	2.66	2.24	2.24	1.96
8-15	8.15	7.28	5.60	3.81	2.72	2.66	2.10	2.10	--	2.10
8-19	11.3	8.48	7.56	6.02	4.20	3.16	2.13	1.96	1.57	1.81
8-26	9.10	7.56	7.42	4.78	3.36	2.97	2.86	2.66	2.58	2.41
9-9	16.0	--	--	--	--	--	--	--	--	--
9-16	26.3	22.0	19.3	16.8	11.7	9.29	8.68	5.04	4.20	3.36
9-23	24.9	21.8	20.5	16.5	12.3	10.6	7.56	5.10	4.81	3.11

TABLE 56

TRICKLING FILTER DATA

Percentage Reduction in Total Nitrogen by Depth and Date

Date	1/2'	1'	2'	3'	4'	5'	6'	7'	8'
3-4	--	--	--	36.2	62.8	--	--	68.7	--
3-13	--	23.8	37.0	40.7	59.2	70.3	79.6	83.3	87.0
3-21	9.70	15.2	20.0	39.6	52.5	55.9	62.2	67.8	77.9
4-11	17.2	24.6	36.8	41.8	73.0	74.2	84.0	84.0	84.0
4-18	18.2	24.2	34.2	35.6	62.8	65.3	82.7	82.7	85.1
4-25	6.21	12.4	32.6	39.4	55.6	70.3	75.3	69.1	78.8
5-10	19.4	--	36.9	51.0	70.2	74.6	80.8	86.0	86.0
5-20	3.24	15.1	37.3	51.6	68.2	74.3	81.8	81.8	86.4
6-3	16.9	25.3	38.3	54.5	69.1	74.5	76.4	89.1	89.1
6-10	9.09	19.6	35.4	52.9	72.6	84.3	84.3	86.3	92.2

TABLE 56 -- (Continued)

Date	1/2'	1'	2'	3'	4'	5'	6'	7'	8'
6-17	10.7	20.0	40.6	50.0	64.0	74.0	79.0	84.8	86.0
7-8	16.4	22.6	38.5	49.7	64.8	74.9	78.5	82.1	85.6
7-15	7.24	25.7	43.5	57.6	53.0	69.1	68.7	83.4	81.6
7-22	6.67	22.5	44.5	54.5	69.7	77.8	81.3	81.3	83.7
8-15	10.7	31.3	53.2	66.6	67.4	74.2	74.2	--	74.2
8-19	24.7	32.9	46.5	62.7	71.9	81.1	82.6	86.1	83.9
8-26	16.9	18.5	47.5	63.1	67.4	68.6	70.8	71.6	73.5
9-16	16.4	26.6	36.1	55.5	64.7	67.0	80.8	84.0	87.2
9-23	12.5	17.7	33.7	50.6	57.4	69.6	79.5	80.7	87.5
Average	13.1	22.2	38.5	50.2	64.5	72.2	77.9	80.7	83.9

TABLE 57

TRICKLING FILTER DATA

Nitrates in mg/l by Depth and Date

Date	0'	1/2'	1'	2'	3'	4'	5'	6'	7'	8'
3-4	0.10	<0.10	0.15	1.60	2.56	5.00	5.28	7.07	8.64	9.37
3-21	<0.10	0.10	0.30	1.28	3.00	4.40	4.70	6.40	7.50	8.30
4-18	<0.10	0.10	0.25	0.95	2.90	3.90	5.05	8.30	8.70	8.80
4-25	<0.10	0.18	0.40	0.80	2.85	3.80	6.20	7.50	7.90	8.60
5-10	<0.10	<0.10	<0.10	1.04	4.60	6.40	7.90	9.20	9.25	10.2
5-20	0.16	0.22	0.32	1.00	4.25	7.85	10.4	11.8	11.4	11.0
6-3	<0.10	0.12	1.13	3.90	7.10	8.70	9.95	11.4	11.1	--
6-10	0.22	0.38	1.58	4.50	7.40	7.65	10.4	9.30	8.85	9.60
6-17	--	<0.10	0.82	2.75	4.78	5.80	6.45	7.20	7.75	10.6

TABLE 57 -- (Continued)

Date	0'	1/2'	1'	2'	3'	4'	5'	6'	7'	8'
7-8	0.12	0.20	0.50	2.95	7.15	8.10	9.70	10.0	9.90	11.4
7-15	0.14	0.18	0.97	4.75	7.90	8.38	9.25	10.8	10.9	11.2
7-22	0.16	0.36	1.24	4.10	6.60	7.90	8.50	--	--	9.00
8-15	0.14	0.14	0.60	2.45	4.20	4.50	4.55	6.50	7.20	7.60
8-19	<0.10	0.32	1.34	3.50	4.90	6.20	7.35	7.60	8.00	8.30
8-26	<0.10	0.18	1.12	2.80	4.95	5.12	5.80	6.55	6.55	6.93
9-9	<0.10	<0.10	1.04	3.90	8.70	9.45	9.65	10.8	13.0	13.2
9-16	<0.10	<0.10	0.16	1.95	6.90	9.10	12.2	11.8	12.2	12.1
9-23	<0.10	<0.10	0.64	4.96	8.89	10.6	11.8	12.8	13.1	13.6

TABLE 58

TRICKLING FILTER DATA

Percentage Nitrification by Depth and Date

Date	0'	1/2'	1'	2'	3'	4'	5'	6'	7'	8'
3-4	0.53	<0.50	0.80	8.51	13.6	26.6	28.1	37.6	46.0	49.8
3-21	<0.60	0.61	1.82	7.76	18.2	26.7	28.5	38.8	45.5	50.3
4-18	<0.80	0.88	2.21	8.41	25.7	34.5	44.7	73.5	77.0	77.9
4-25	<0.70	1.24	2.76	5.52	19.7	26.2	42.8	51.7	54.5	59.3
5-10	<0.60	<0.60	0.60	6.50	28.8	40.0	49.4	57.5	57.8	63.8
5-20	0.86	1.19	1.73	5.41	23.0	42.4	56.2	63.8	61.6	59.5
6-3	<0.60	0.78	7.34	25.3	46.1	56.5	64.6	74.0	72.1	--
6-10	1.54	2.66	11.0	31.5	51.7	53.5	72.7	65.0	61.9	67.1
6-17	--	<0.70	5.86	19.6	34.1	41.4	46.1	51.4	55.4	75.7

TABLE 58 -- (Continued)

Date	0'	1/2'	1'	2'	3'	4'	5'	6'	7'	8'
7-8	0.62	1.03	2.56	15.1	36.7	41.5	49.7	51.3	50.8	58.5
7-15	0.92	1.18	6.38	31.2	52.0	55.1	60.9	71.1	71.7	73.7
7-22	1.33	3.00	10.3	34.2	55.0	65.8	70.8	--	--	75.0
8-15	1.72	1.72	7.36	30.1	51.5	55.2	55.8	79.8	88.3	93.3
8-19	<0.90	2.83	11.9	31.0	43.4	54.9	65.0	67.3	70.8	73.5
8-26	<1.10	1.98	12.3	30.8	54.4	56.3	63.7	72.0	72.0	76.2
9-9	<0.70	<0.70	6.52	24.4	54.5	59.2	60.5	67.7	81.5	82.7
9-16	<0.40	<0.40	0.61	7.41	26.2	34.6	46.4	44.9	46.4	46.0
9-23	<0.40	<0.40	2.57	19.9	35.7	42.6	47.4	51.4	52.6	54.6
Average	<0.84	<1.24	5.26	19.0	37.2	45.2	53.0	59.9	62.7	66.9

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The author was born in Black, Alabama on January 2, 1937. Shortly thereafter, he moved to Marianna, Florida where he received his secondary education. He entered Chipola Junior College in September, 1955, and received an Associate in Arts degree in June, 1957. Undergraduate studies were continued at the University of Florida where the degree Bachelor of Civil Engineering with Honors was conferred June 6, 1960. Shortly after graduation he entered the graduate school at the University of Florida and was awarded the degree Master of Science in Engineering on August 12, 1961.

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This dissertation was prepared under the direction of the chairman of the candidate's supervisory committee and has been approved by all members of that committee. It was submitted to the Dean of the College of Engineering and to the Graduate Council and was approved as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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